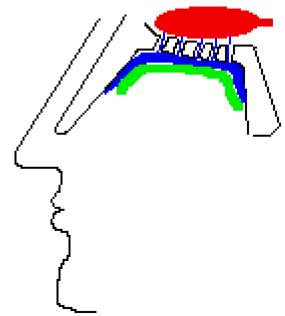
Particle Identification, Trigger & Modern Detectors

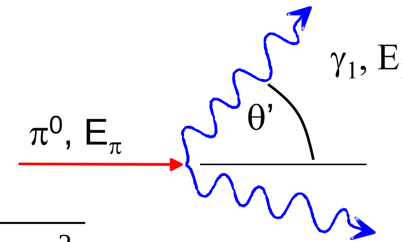


- Particle Identification
  - Neutral particles
  - Methods for charged particles
- Trigger
  - Basics
  - Modern Example
- not presented: Modern Detectors
  - “slide show”

Stephan Eisenhardt

π^0

- **lightest neutral hadron:**
  - life time: τ=0.084fs ($\pi^\pm$: τ=26ns)
  - decay: $\pi^0 \to \gamma\gamma$; BR = 98.798%
  - γ energy and angle:



$$E_\gamma = \frac{1}{2} E_\pi (1 + \beta \cos\theta_{CMS}) \qquad \beta = \sqrt{1 - \frac{m_\pi^2}{E_\pi^2}}$$

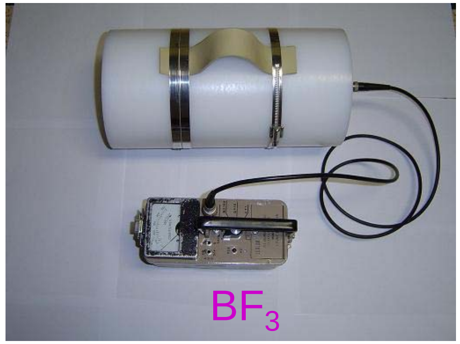
  - $J_\pi = 0 \to$ isotropic θ distribution in CMS
  - deterministic kinematics
  - reconstruction from el.mag. showers induced by the 2γ:
    - needs el.mag. calorimeter: $E_{\gamma 1}$, $E_{\gamma 2}$
    - disparity: D > 3 for 50%, D > 7 for 25%
    - good angular resolution: distance d $\to$ angle θ
    - for π^0 hypothesis: use mass restriction $m_{\pi 0}$=135MeV

$$D = \frac{E_1}{E_2} \approx \frac{1 + \cos\theta}{1 - \cos\theta} \quad \text{for} \quad \beta \to 1$$

- **heavier neutral hadrons:**
  - long living: neutron
  - short living: η, ρ^0, ω, ϕ, K_S^0(90fs), [K_L^0(51ns)], D^0(0.41ps), B^0(1.5ps), Δ, Λ, Σ, Ξ, …
    - reconstructed kinematically from secondary particles : π^0, γ & charged particles

Neutron Counters

- no direct detection possible → 4 main methods:
  - thermal n: neutron activation reactions, e.g. $^{63}Cu(n,\gamma)^{64}Cu$ → measure delayed γ
  - E_n < 20MeV: prompt nuclear reactions with charged secondaries
  - E_n < 1GeV: elastic scattering of n or p → measure recoil partner
  - E_n > 5GeV: cascade of inelastic scatterings → calorimeter



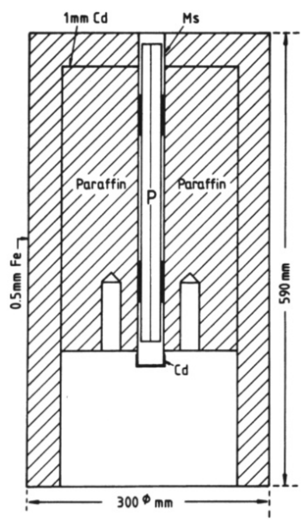
BF$_3$
10keV-10MeV

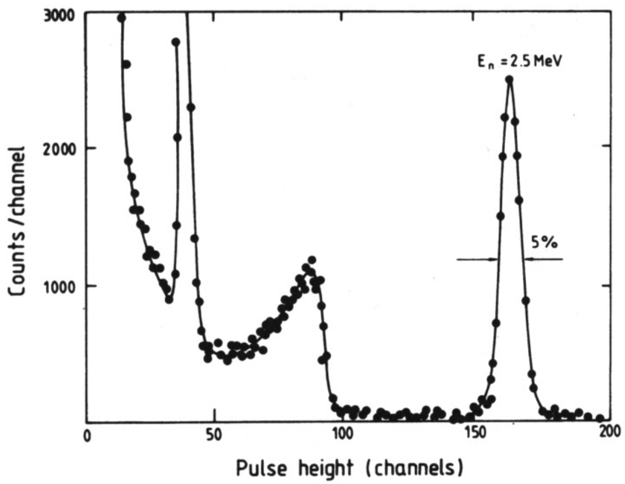
- neutron monitor:
  - up to 20MeV
  - uses paraffin (H2 rich) as moderator to thermalise neutrons
    → large cross section for prompt nuclear reactions (1-1000 barn)

    $n+^{6}Li \rightarrow \alpha+^{3}H$

    $n+^{10}B \rightarrow \alpha+^{7}Li$

    $n+^{3}He \rightarrow p+^{3}H$
  - use e.g. BF$_3$ gas counter





^{3}He + Krypton proportional counter: neutrons (2.5MeV)

Time of Flight Measurement

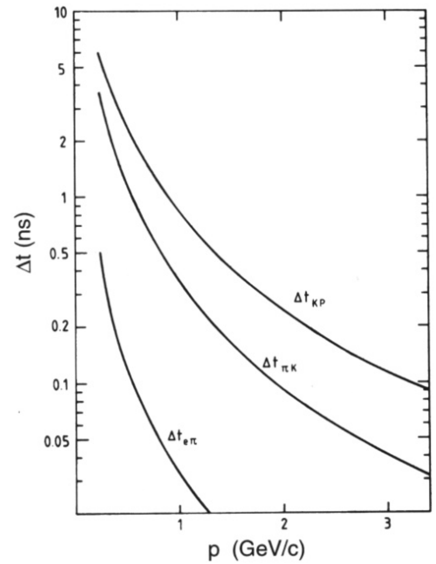
- particle identification through flight time:

$$\Delta t = \frac{L}{\beta_1 c} - \frac{L}{\beta_2 c} = \frac{L}{c}\left[\sqrt{1+\frac{m_1^2c^2}{P^2}} - \sqrt{1+\frac{m_2^2c^2}{P^2}}\right] \approx \frac{Lc\left(m_1^2 - m_2^2\right)}{2P^2} \quad \textit{for } P^2 >> m^2c^2$$

- time resolution:
  - σ_t=300ps for organic scintillation counter
  - σ_t=50ps for parallel-plate counter
- $4\sigma_t$ separation : σ_t=300ps σ_t=50ps

	σ_t=300ps	σ_t=50ps
π-K @ 1GeV	3.4m	0.6m
π-K @ 2GeV	13m	2.2m
e-π @ 200MeV	1.0m	0.16m
e-π @ 400MeV	6.0m	1.0m

time-of-flight differences for 1m

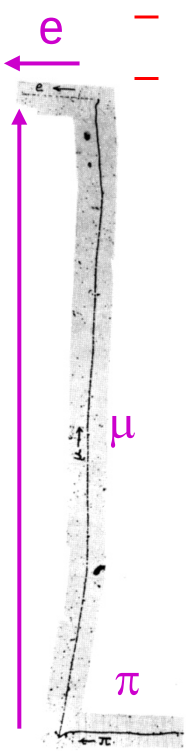


➔ method limited to low momenta (<2GeV/c)

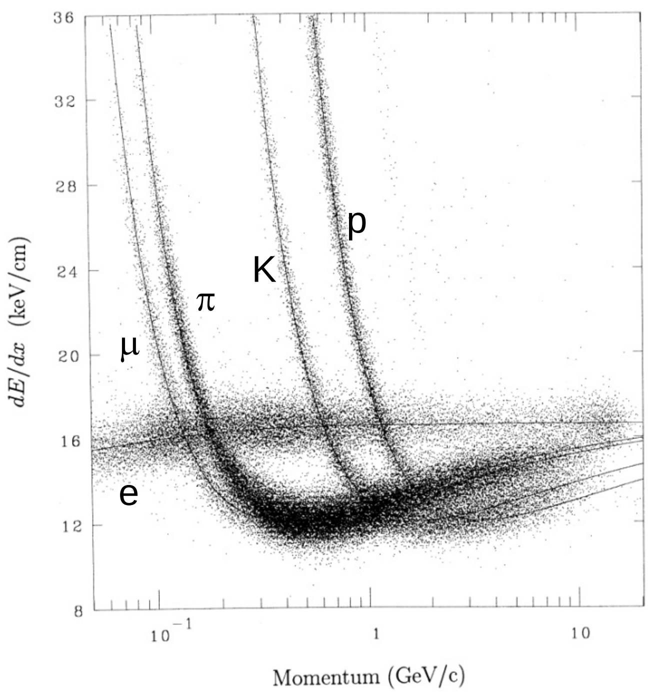
COSY TOF barrel & end cap

dE/dx

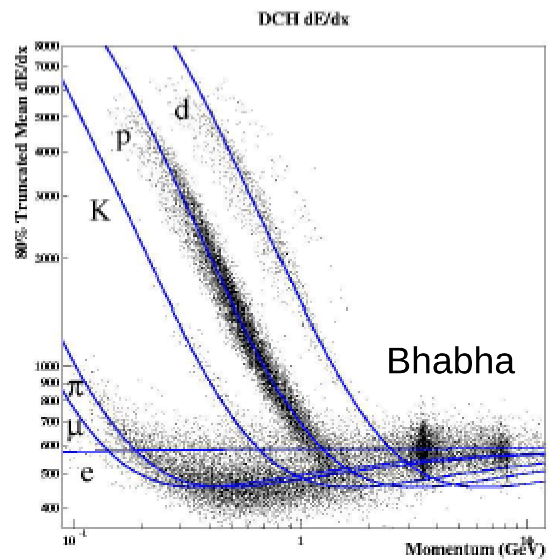
- Low energy range:
  - heavier particles polarise medium stronger → larger energy loss via ionisation
  - Bethe-Bloch: dE/dx rises strongly for p<m [GeV]
  - used in emulsions, cloud & bubble chambers and tracking chambers
  - several samples taken per track: increased efficiency
  - “multiple ionisation measurement” in region of relativistic rise



emulsion



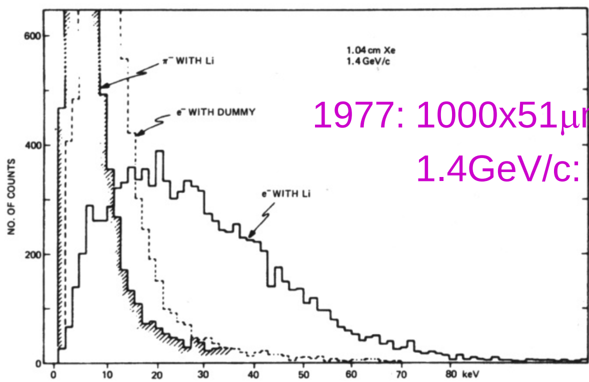
Two Gamma TPC



BaBar drift chamber

Transition Radiation

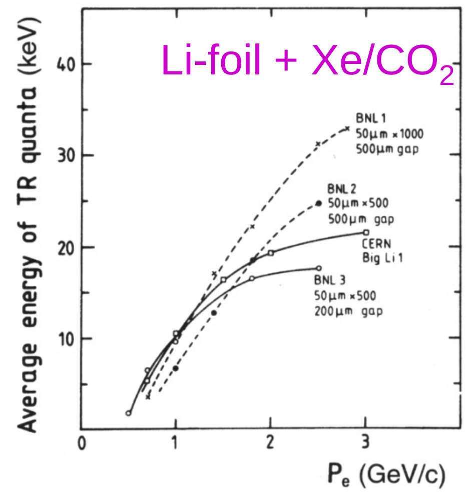
- X-ray regime:
  - $\varepsilon=n^2$; $\varepsilon=\varepsilon_1+i\varepsilon_2$; $\varepsilon_1<1$; $\varepsilon_2<<1$: $v>v_C$, i.e. below Cherenkov radiation threshold
  - but still photons emitted at n-boundaries, i.e. change in dielectric constant
  - charge in vacuum and mirror charge in medium form moving dipole → el.mag. “TR”
- periodic radiator + detector, e.g. proportional chamber:
  - intensity ~ γ, concentrated in half opening angle $\phi \sim 1/\gamma$ $\gamma=E/mc^2$
  - periodic arragement: foils or air gaps → interference → threshold in γ
  - X-ray absorption ~ $Z^{3.5}$ → low Z radiator needed → best candidate: Li



1977: 1000x51μm Li-foils, Xe detector

1.4GeV/c: π: $\gamma=10$, e^-: $\gamma=2740$

Li-foil + Xe/CO_2 80:20



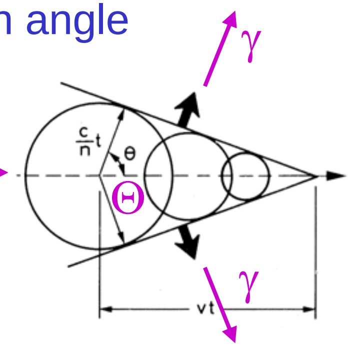
  - usable range: $\gamma>1000$, i.e. $E_e>0.5$GeV/c, $E_\pi>140$GeV/c
  - for $\gamma<1000$: 1-5keV X-ray radiation detection is needed
  - alternative: 12x(n 35μm Li-foils + Xe chamber): $\varepsilon_{e-}=90\%$, π-rejection:8×10^{-4}
  - $\varepsilon_\pi=90\%$, K-rejection:10^{-2}

Recap: Threshold Cherenkov Counter

- particle identification through velocity measurement:
  - for charged particles: $\beta c = v > \frac{c}{n}$
- 'shock-wave': coherent wave front with angle

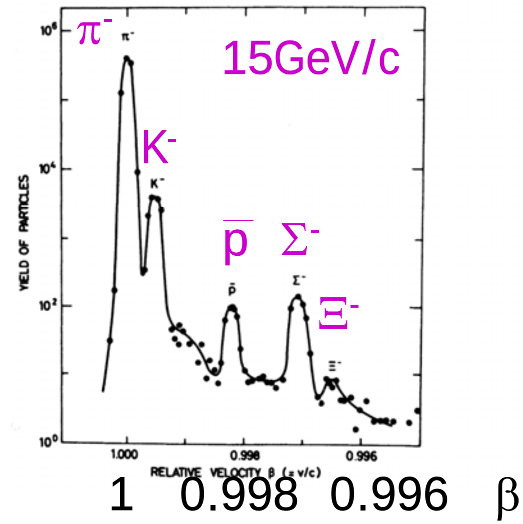
$$\cos\theta_C = \frac{1}{\beta n(\omega)}$$

  + finite radiator effects
  ➔ directed photon signal



- use: p=mv
- concepts:
  - threshold counter
  - differential counter
  - ring imaging

Fig. 5.11. Velocity distribution of charged hyperons with 15 GeV/c momentum in a short secondary beam [LI 73].



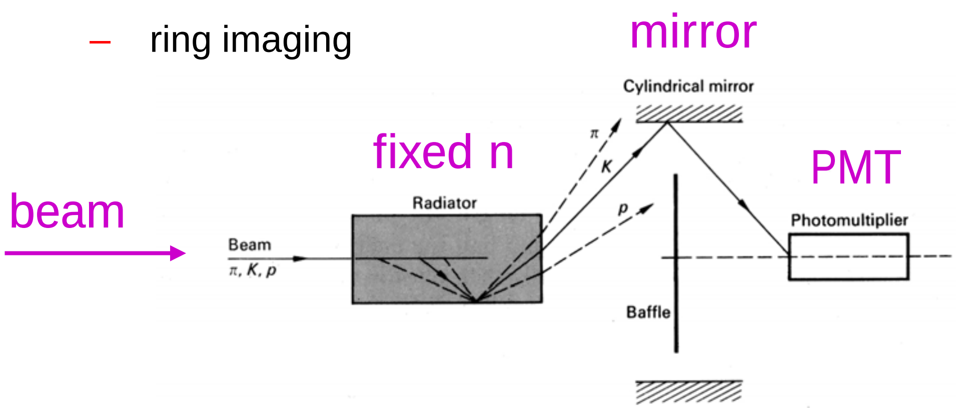
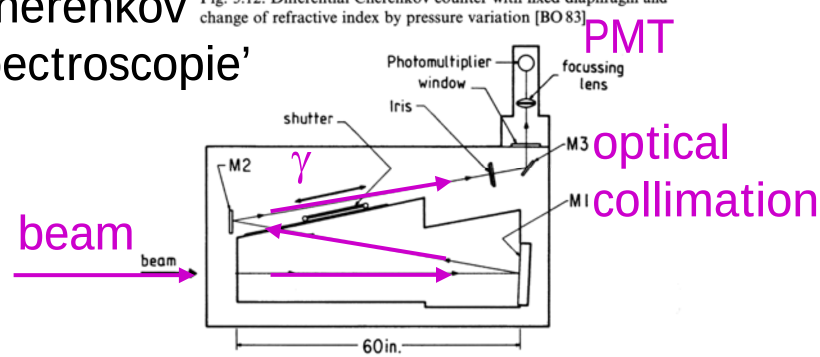


Figure 2.18 Early design of differential Čerenkov counter. The arrangement is intended to select light from one of three components of the beam (K-mesons, in the case shown).

'Cherenkov spectroscopie'

Fig. 5.12. Differential Cherenkov counter with fixed diaphragm and change of refractive index by pressure variation [BO 83]



variable pressure: n(P)

Cherenkov Counter - Details

- angular distribution of radiation:
  - produced photons: N
  - maxima due to diffraction
  - for a long radiator: L>>λ

$$\frac{d^2N}{d\lambda d\cos\theta} = \frac{2\pi\alpha}{\lambda}\left(\frac{L}{\lambda}\right)^2\left(\frac{\sin x}{x}\right)^2\sin^2\theta \qquad x(\theta)=\frac{\pi\lambda}{L}\left[\frac{1}{n\beta}-\cos\theta\right]$$

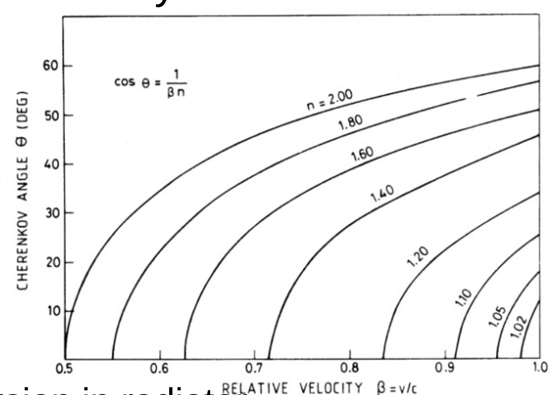
$$\frac{dN}{d\lambda} \approx \frac{2\pi\alpha}{\lambda^2}L\sin^2\theta_C$$

  - number of produced photons: flat in energy!!

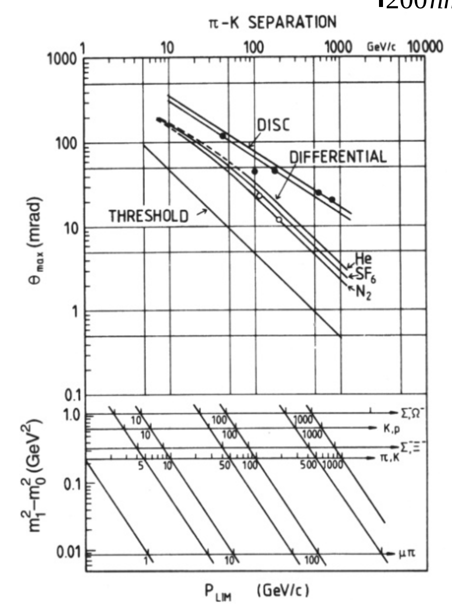
$$\frac{N}{1cm} = 490\sin^2\theta_C\Big|_{400nm}^{700nm} = 870\sin^2\theta_C\Big|_{300nm}^{700nm} = 1630\sin^2\theta_C\Big|_{200nm}^{700nm}$$

$$N = 2\pi\alpha L\int_{\lambda_2}^{\lambda_1}\frac{\sin^2\theta_C}{\lambda^2}d\lambda = \frac{2\pi\alpha L}{\hbar c}\int_{E_1}^{E_2}\sin^2\theta_C dE \;\; ; \;\; c=\lambda\nu \;\; ; \;\; E=\hbar\nu$$

  - figure of merit : $N_{eff} = \varepsilon$ N , with detector efficiency ε



- Counter types:
  - threshold:
    - limited by choice of material & momentum
  - differential:
    - better selection → better separation
  - DISC:
    - differential, correcting for chromatic dispersion in radiator
    - achieved: $\Delta\beta/\beta \sim 10^{-7}$ → π-K separation up to 500GeV/c



- Problem: only for particles parallel to optical axis of detector, i.e. along beam line

Cherenkov Media

- chose material n to match separation of $m_1<m_2$:
  - heavier particle m_2 does not yet radiate
  - or is just below threshold: $\beta_2<1/n$
- selection of radiator materials:
  - gases at normal conditions
  - Aerogel fills gap between gases and solids/fluids
- example light yield:
  - e.g. π-K separation
  - radiator: L=1m of C_4F_{10}
  - thresholds in C_4F_{10}: E_π = 2.6GeV; E_K = 9.3GeV
  - <QE> of photodetector: ε_{QE} = 0.2
  - detector efficiency: ε_D
  - light yield:
    - π @ 9GeV: $\rightarrow \beta_\pi$=0.999879 $\rightarrow \theta_\pi$=50mrad

$$N = \varepsilon_{QE}\varepsilon_D L \cdot 870 \sin^2\theta_C \Big|_{300nm}^{700nm} = \varepsilon_{QE}\varepsilon_D \cdot 220 = \varepsilon_D \cdot 44$$

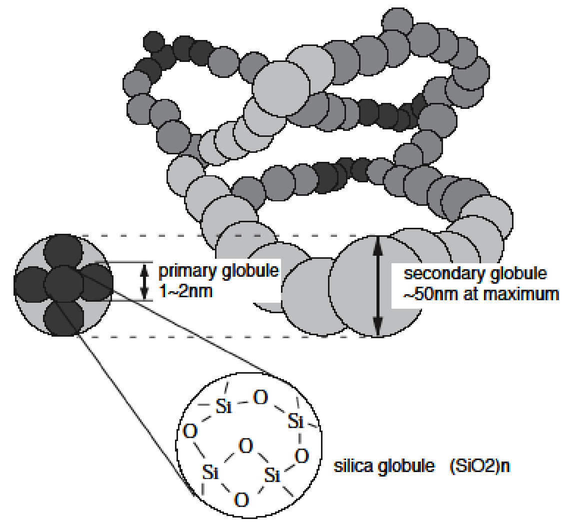
    - π @ 10GeV: $\rightarrow \beta_\pi$=0.999902 $\rightarrow \theta_\pi$=51mrad $\quad N = \varepsilon_{QE}\varepsilon_D \cdot 226 = \varepsilon_D \cdot 45.2$
    - K @ 10GeV: $\rightarrow \beta_K$=0.998780 $\rightarrow \theta_K$=19mrad $\quad N = \varepsilon_{QE}\varepsilon_D \cdot 31 = \varepsilon_D \cdot 6.2$

medium	n	γ_s (threshold)	β_s (threshold)
Diamond	2.42	1.10	0.41
ZnS(Ag)	2.37	1.10	0.42
lead fluoride	1.80	1.20	0.56
Glass	1.46-1.75	1.22-1.37	0.57-0.68
Scintillator (toluene)	1.58	1.29	0.63
Plexiglas (acrylic)	1.48	1.36	0.68
Water	1.33	1.52	0.75
Aerogel	1.025-1.075	2.7-4.5	0.93-0.976
Pentane	1.0017	17.2	0.9983
C_4F_{10}	1.0014	18.9	0.9986
CF_4	1.00050	31.6	0.9995
CO_2	1.00043	34.1	0.9996
He	1.000033	123	0.99997

$$\beta^2 = 1 - \frac{m^2c^4}{E^2} \qquad \gamma^2 = \frac{1}{1-\beta^2}$$

Aerogel I

- structure: $n(SiO_2)+2n(H_2O)$
  - "foamed silicon" → light: 22 litres = 3 kg
  - baked out in tiles of up to ~15x15x6cm³



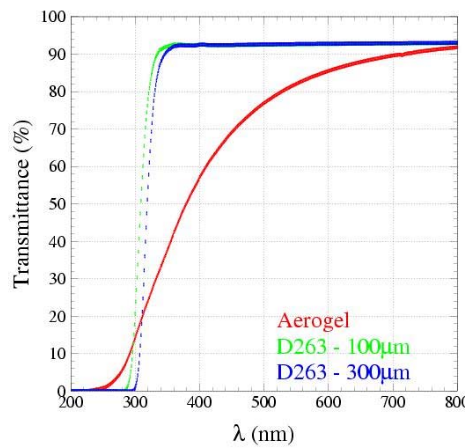
- production: sol-gel process

$$nSi(OR)_4 + 4nH_2O \rightarrow nSi(OH)_4 + 4nH_2O \quad \text{hydrolysis}$$
$$nSi(OH)_4 \rightarrow (SiO_2)_n + 2nH_2O \quad \text{condensation}$$

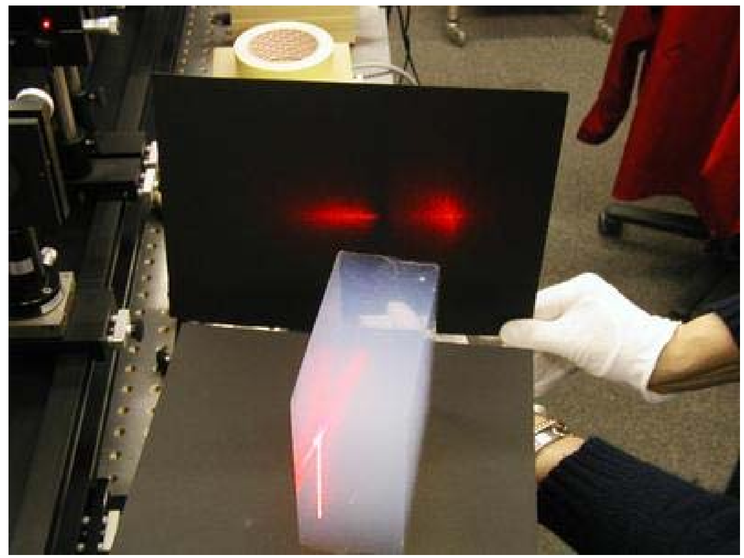
  - chemical treatment to make hydrophobic
  - supercritical drying: CO_2 extraction method (31°C, 7.5 MPa)

- transmission T:
  - exponential λ^4 dependence:

$$T = Ae^{\left(-\frac{Cx}{\lambda^4}\right)}$$

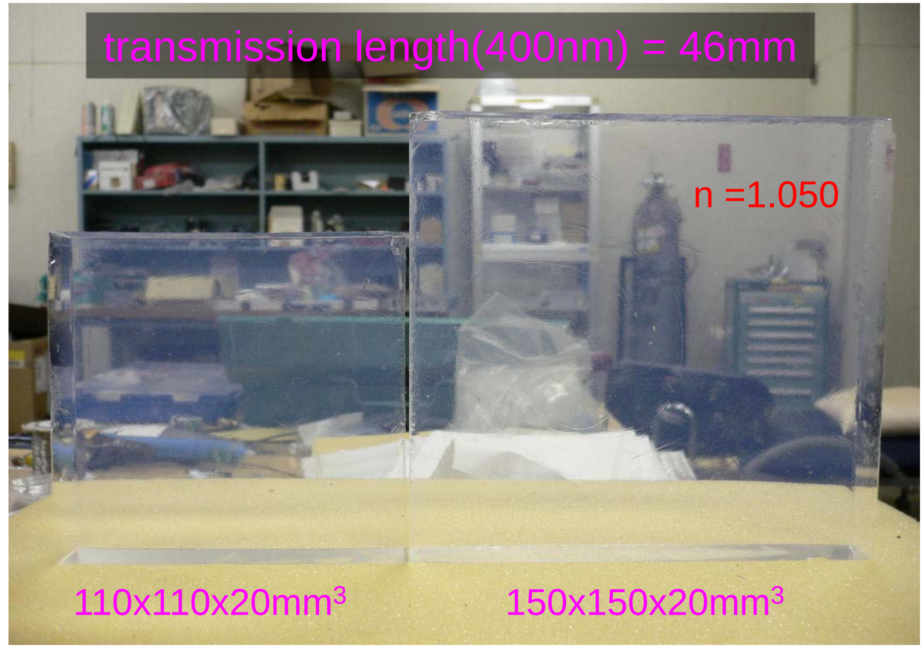


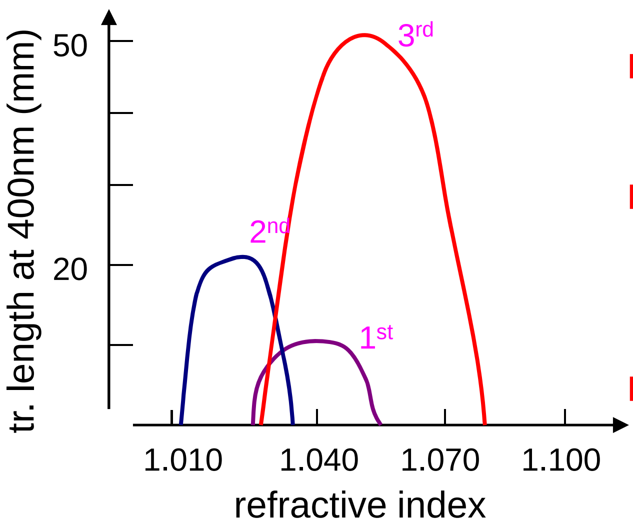
  - limited by Rayleigh scattering
  - red emission dominant



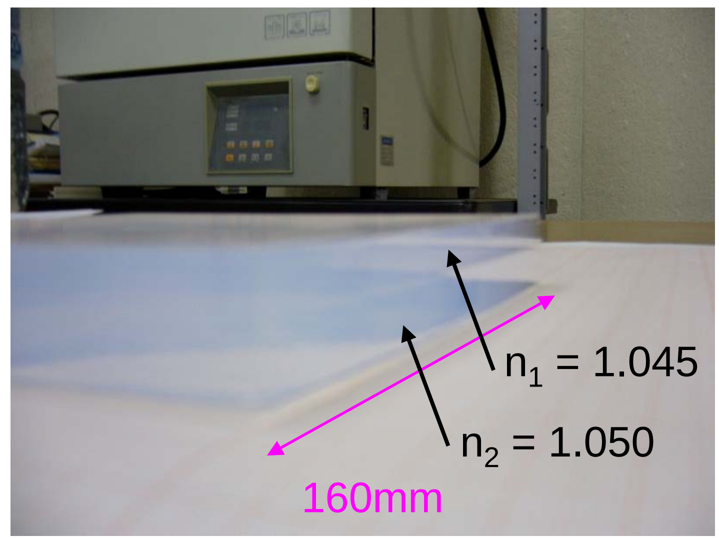
Aerogel II

- clarity C: (with n=1.030±0.001 @ 400nm)
  - Matsushita (hydrophobic): C ~ 0.009 μm⁴ cm⁻¹ → 5
  - Novosibirsk (hydroscopic): C ~ 0.005 μm⁴ cm⁻¹
    - larger tiles
    - higher yield of unscattered photons
    - but more difficult to handle
- new developments:
  - higher index aerogels
  - stacking of 2…3 different indices for better proximity focussing





- 1^{st} generation: 70's-80's
  - n = 1.025-1.055
- 2^{nd} generation: 1992-2002
  - n = 1.010…1.030
  - new: hydrophobic
- 3^{rd} generation: 2002-
  - n = 1.030…1.080
  - new: solvent

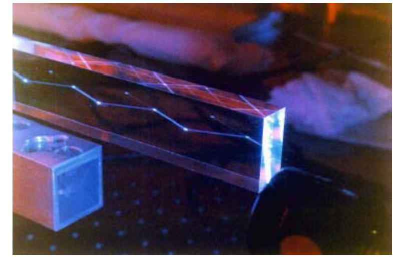


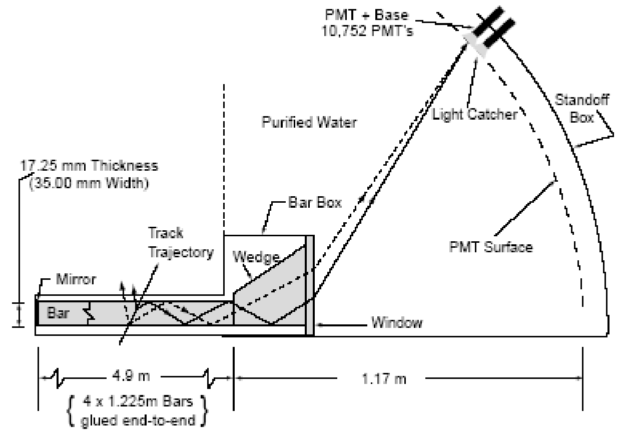
DIRC

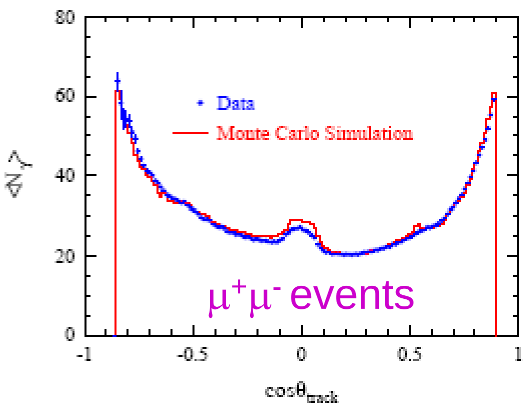
- BaBar: Detector of Internally Reflected Cherenkov light:
  - 144 quartz rods, $1.7\text{x}3.5\text{x}490\text{cm}^3$, highest grade optical polish
  - angle of Cherenkov light wrt. track conserved
  - glued to quartz wedges to fold image
  - 6000l pure H_2O expansion tank ($n_{H2O} \sim n_{quartz}$)
  - readout: 10752 PMT
  - single photon resolution: $\sigma_{C,\gamma} = 10.2\text{mrad}$

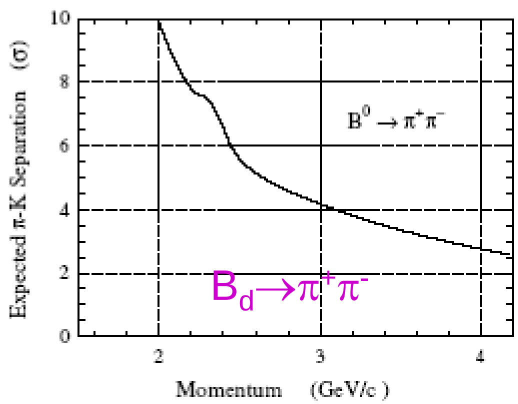
    $\sigma_{t,\gamma} = 1.7\text{ns}$
  - track resolution:

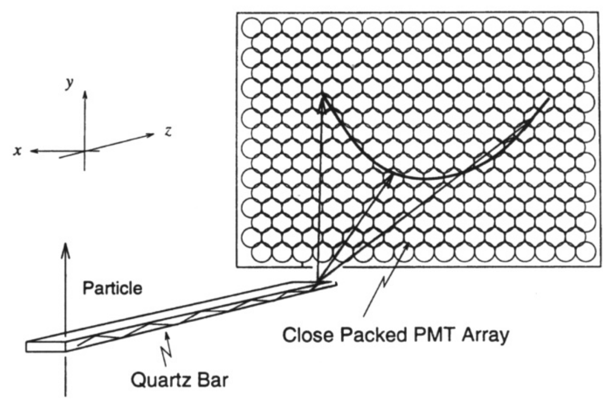
    (for no systematic errors) $\sigma_{track,\gamma} = \frac{\sigma_{C,\gamma}}{\sqrt{N_{pe}}}$
  - photon yield & K-π separation:





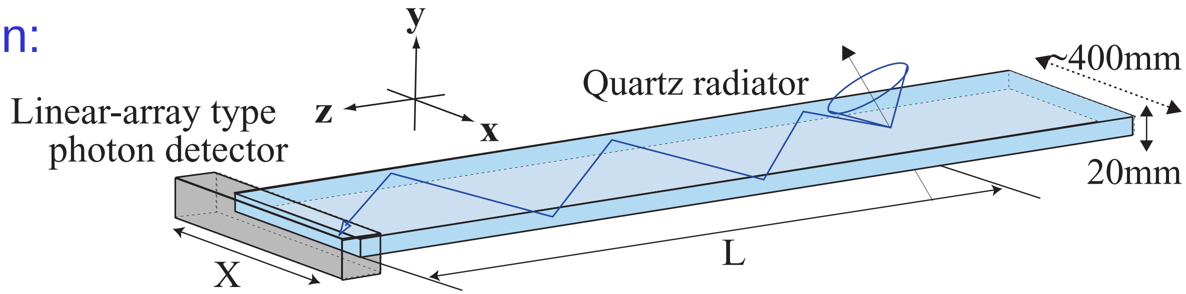


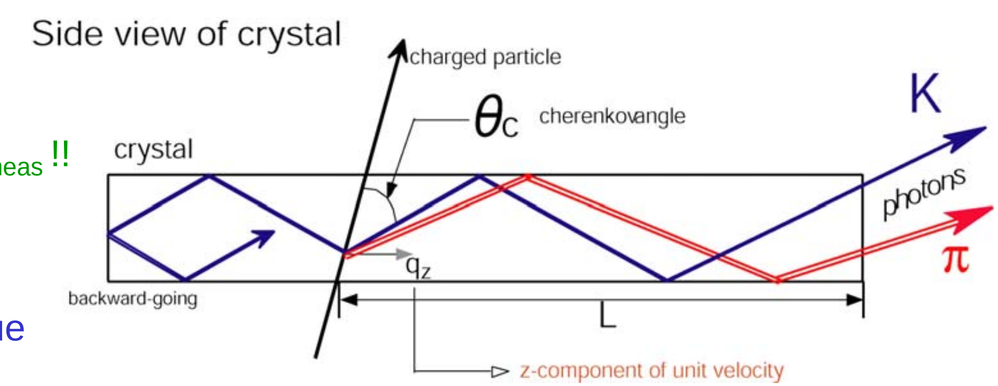


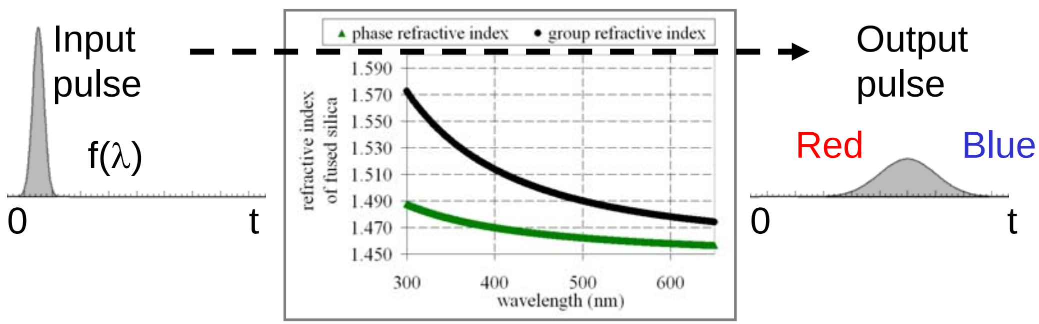


Time of Propagation

- DIRC + propagation time information:
  - 3 processes add in time:
    - TOF from IP
    - TOP in crystal due to path length:
      $L_\pi < L_K$, caused by $\theta_{c,\pi} > \theta_{c,K}$
      Belle upgrade: Barrel TOP: $\Delta t(\pi\text{-}K) \sim 200$ps
    - TOP due to dispersion in optical medium:
      red photons travel faster than blue photons
      fused silica: $\Delta t/L \sim 40$ps/m → correct $\theta_{c,meas}$!!





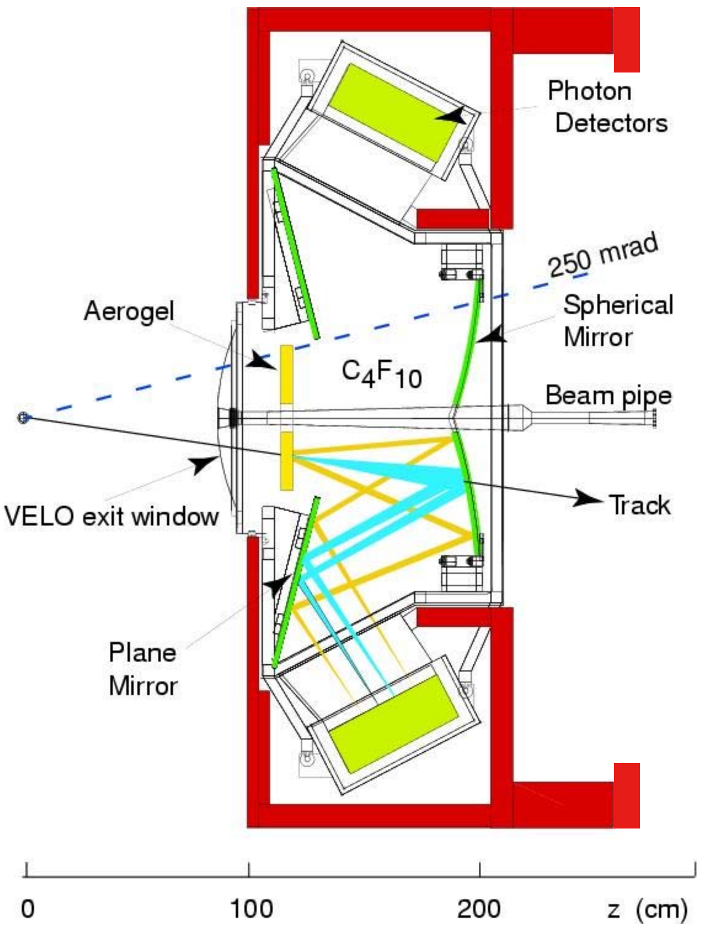


- quest: O(1ps) time resolution!
  - recent testbeam: 27ps (~1 N_{pe}), 7.2ps (~50 N_{pe})

- today's time resolution (of the shelf):
  - Hamamatsu H-9500 Flat Panel MaPMT (256 pixels, 3x12mm pad, σ_{TTS} ~220ps)
  - Hamamatsu H-8500 MaPMT (64 pixels, 6x6mm pad, σ_{TTS} ~140ps)
  - Burle 85011-501 MCP-PMT (64 pixels, 6x6mm pad, σ_{TTS} ~50-70ps)

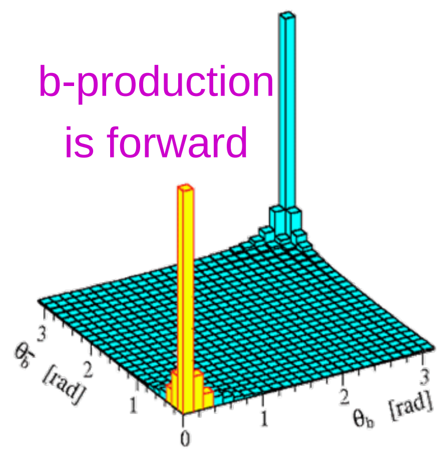
Ring Imaging Cherenkov Counter

RICH1
side view

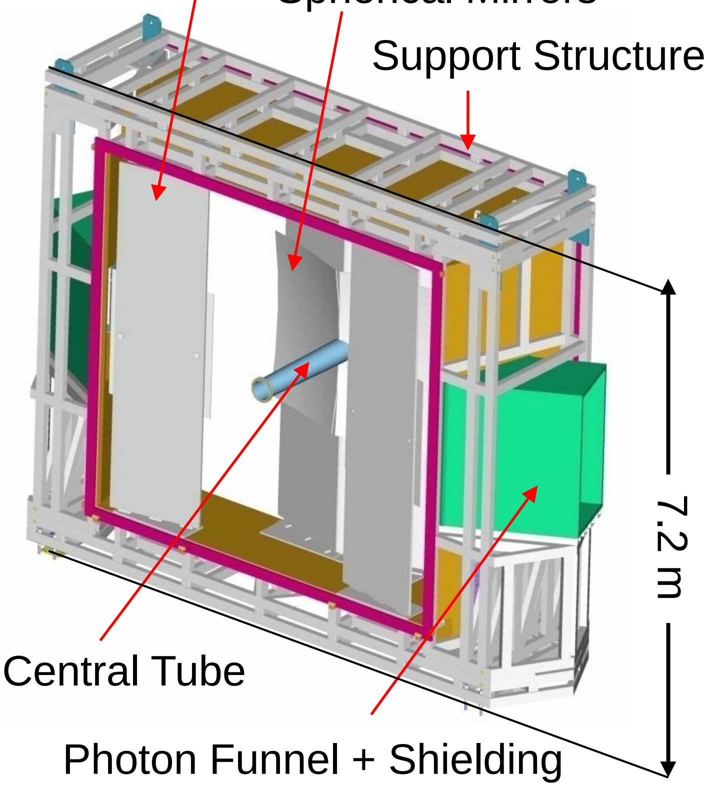


- LHCb RICH:
  3 radiator media:
  aerogel, C_4F_{10}, CF_4
- spherical mirrors:
  focusing→ ring image
  tilt → outside acceptance
- secondary flat mirrors
  → magnetic shielding
- acceptance
  RICH1: 25-300mrad
  RICH2 :15-120mrad

b-production
is forward



RICH2

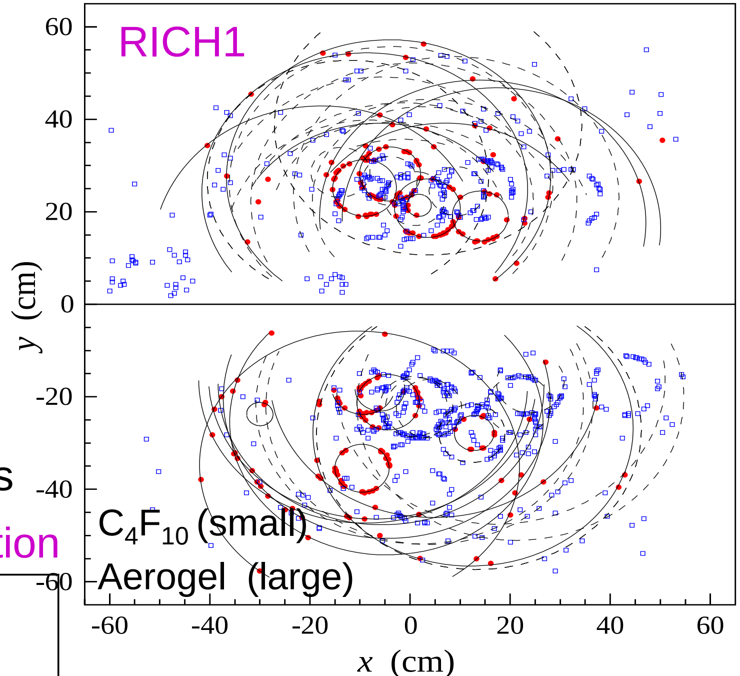


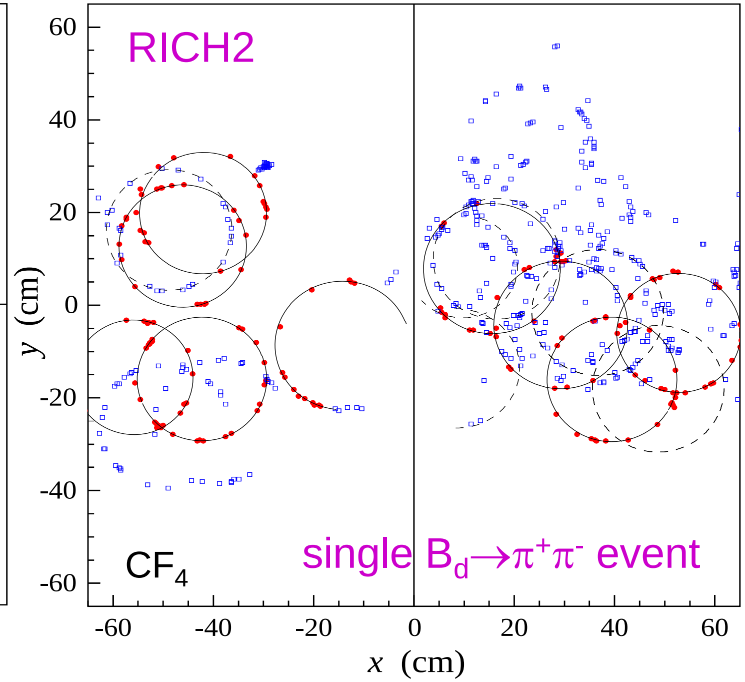
Pattern Recognition

- LHCb RICH detector:
  - find ellipses
  - match to tracks
  - ghosts: no track
  - angle → velocity

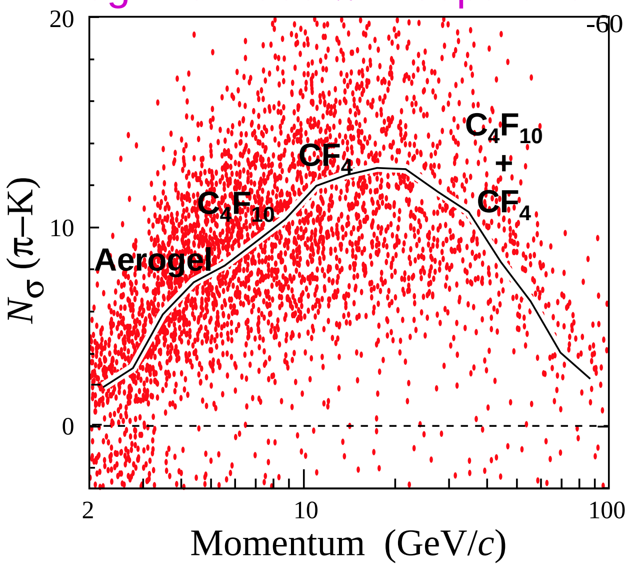
$$\cos(\theta_c) = \frac{1}{n \cdot v/c}$$

  - track mom. → mass





log-likelihood π-K separation



	Cherenkov angle resolution	detected photons
Aerogel	1.82 mrad	6.8
C_4F_{10}	1.27 mrad	30
CF_4	0.59 mrad	23

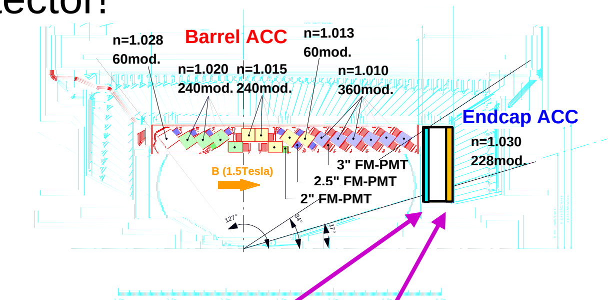
active area fraction

~ 44x0.7x0.99x0.99

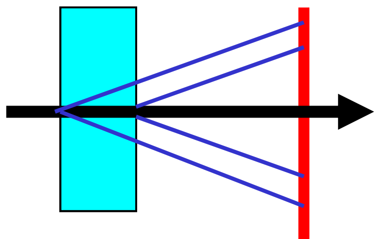
mirror reflectivities

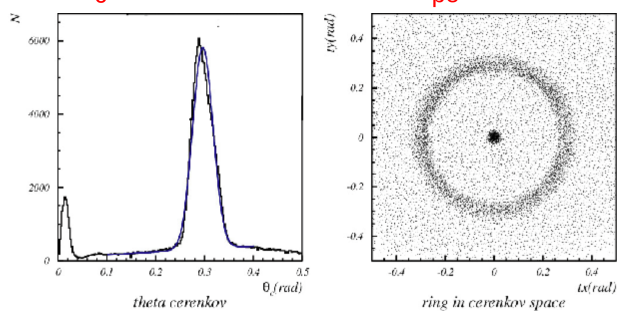
Proximity Focusing RICH

- Belle upgrade: end-cap RICH
  - proximity focusing = compact design $\rightarrow$ usable in storage ring detector!
  - aerogel radiator, gap: O(20cm), high spatial resolution γ detection



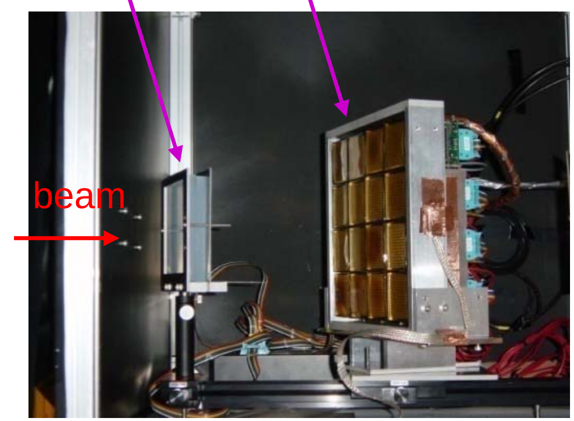
- conventional design:
  - 4cm thick aerogel
  - n=1.047



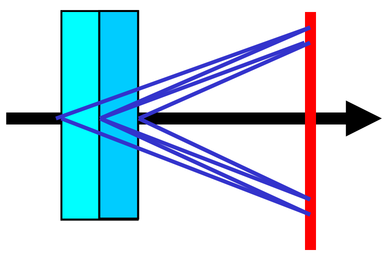


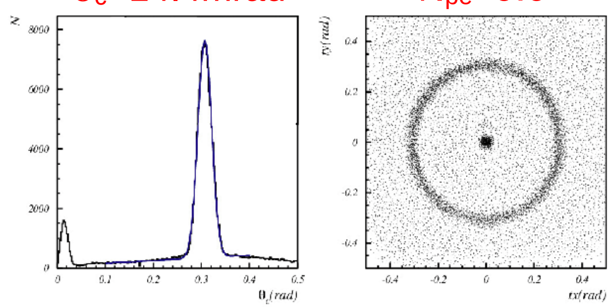
2 layer aerogel

array of flat-panel MaPMT



- multiple radiator design:
  - 2 layers, each 2cm thick
  - n_1=1.047, n_2=1.057

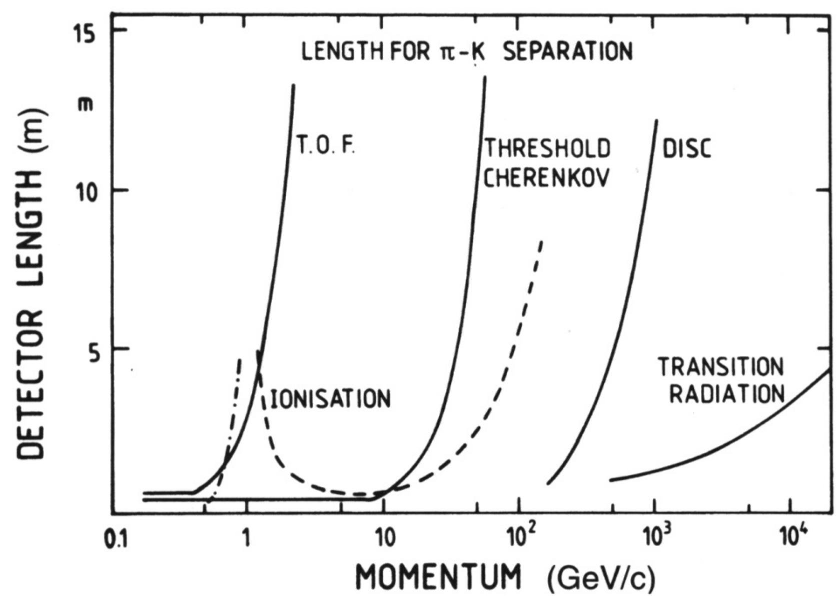




  - π/K separation with focusing configuration: ~ 4.8σ @4GeV/c

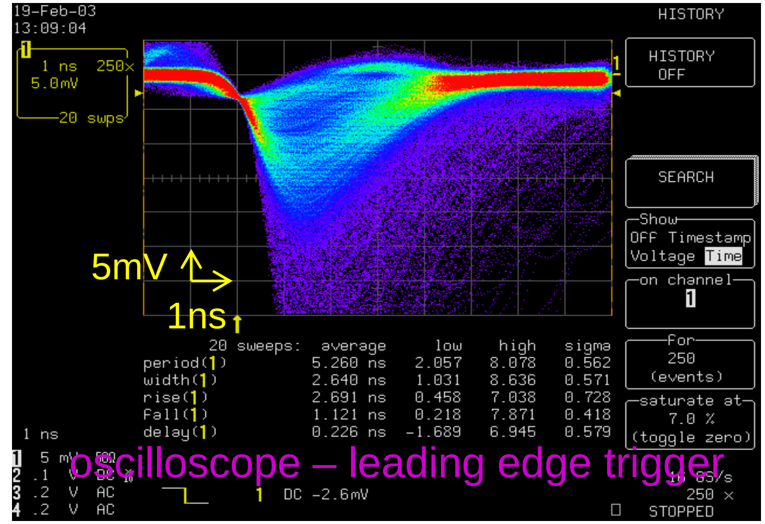
Particle Identification - Summary

method:	momentum range fixed target L=30m	 storage ring L=3m	 requirements
dE/dx	0.2…2GeV/c	0.2…2GeV/c	σ_r=2% (3%) for 30m (3m)
time of flight	<4GeV/c	<1GeV/c	σ_t=300ps
DIRC, TOP	n.a.	2…4GeV/c	highest optical quality surface
Cherenkov threshold	<80GeV/c	<25GeV/c	10 photoelectrons
RICH, prox. focus. RICH	1…150GeV/c	0.7…4.5GeV/c	single γ, O(mrad) resolution
DISC	<2000GeV/c	n.a.	achromatic gas counter
dE/dx multiple ionisation meas.	1.2…100GeV/c	1.5…45GeV/c	σ_r=2% (3%) for 30m (3m)
transition radiation	γ>1000	γ>1000	X-ray detection with E>10keV



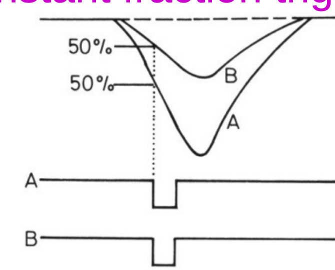
Trigger - Basics

- Trigger:
  - time-stamp for occurrence of defined event
- Walk:
  - variations in amplitude or rise time
    → different rel. timing of leading edge wrt. signal
  - finite amount of charge to trigger discriminator
    → slope dependent excess over threshold needed
- Jitter:
  - noise & statistical fluctuations in signal
    → identical signal don't trigger at the same point

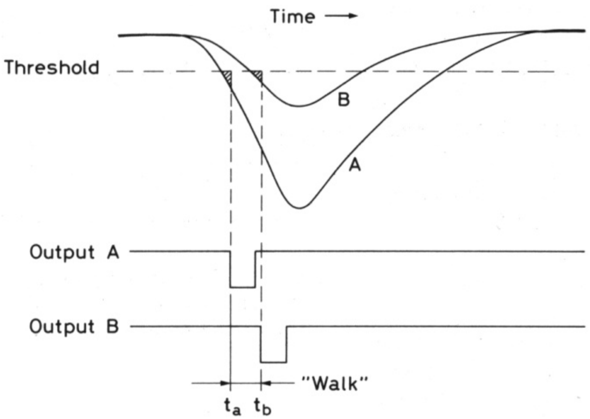


oscilloscope – leading edge trigger

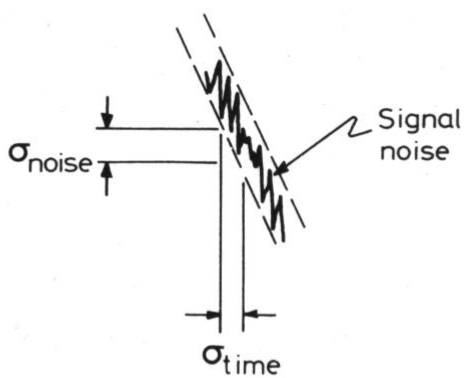
constant fraction trigger



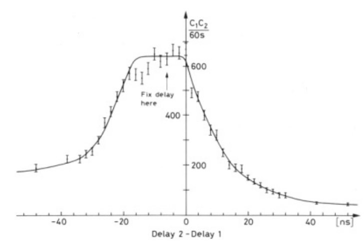
walk



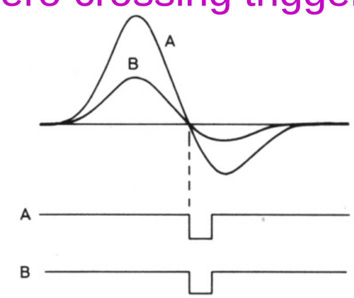
jitter



coincidence curve with finite resolution



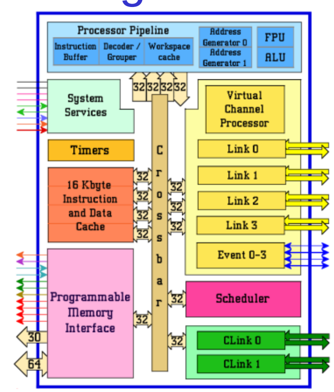
zero crossing trigger



Trigger Concepts

- Electron collider:
  - large cross section for studied processes
  - often: data taking in resonance → "take all" approach
  - i.e. buffer event bursts and write to disc between event bursts → just provide the bandwidth…
- Hadron collider:
  - dominated by background
  - seek "needle in haystack"

    → sophisticated, highly efficient online event selection needed
- Tiered trigger for online event selection: cut background, leave maximum of signal
  - level 0: hardware coded
    - fast: O(μs), deterministic in time
    - e.g. hit multiplicities, (transversal) energy sums for single detector sub systems
  - level 1: hardware or (preferably) software coded
    - factor 10-100 more time, still deterministic in time
    - merging level 0 data for fast detector sub-systems
  - level 2,3: parallel computing
    - event building → physical parameters as offline
    - parallel processing of events, variable time, single event might be time consuming
    - application of "physics filters": cuts on high level parameters as close as possible to offline analysis



1990: transputer

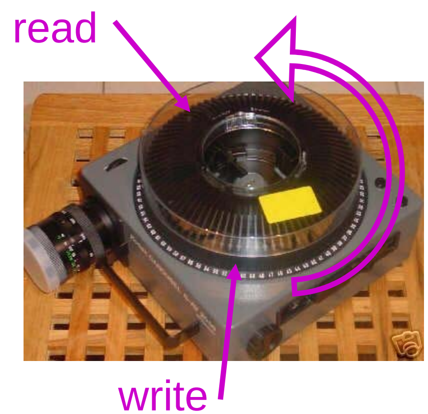
today: PC farm

Dead Time, Latency & Bandwidth

- Accelerator clock:
  - gives time structure for events
  - defines data rate and requirements for data buffering and time to decide
- Dead time:
  - level 0 decision needs longer than clock cycle → may miss valid data for BG event

    → signal buffering: circular pipeline, continuously filled, event readout on L0 trigger
- Latency:
  a) individual event: delay between event and trigger signal
  b) trigger system: maximum allowed time for trigger decision
  - dead time free:

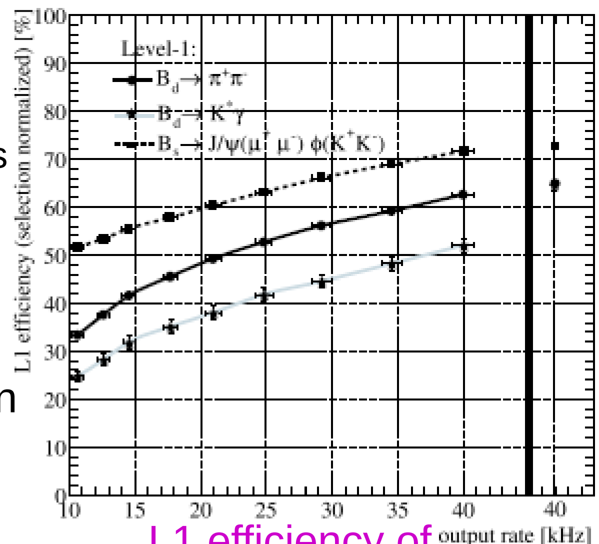
    if trigger decision guaranteed to be faster than one pipeline revolution



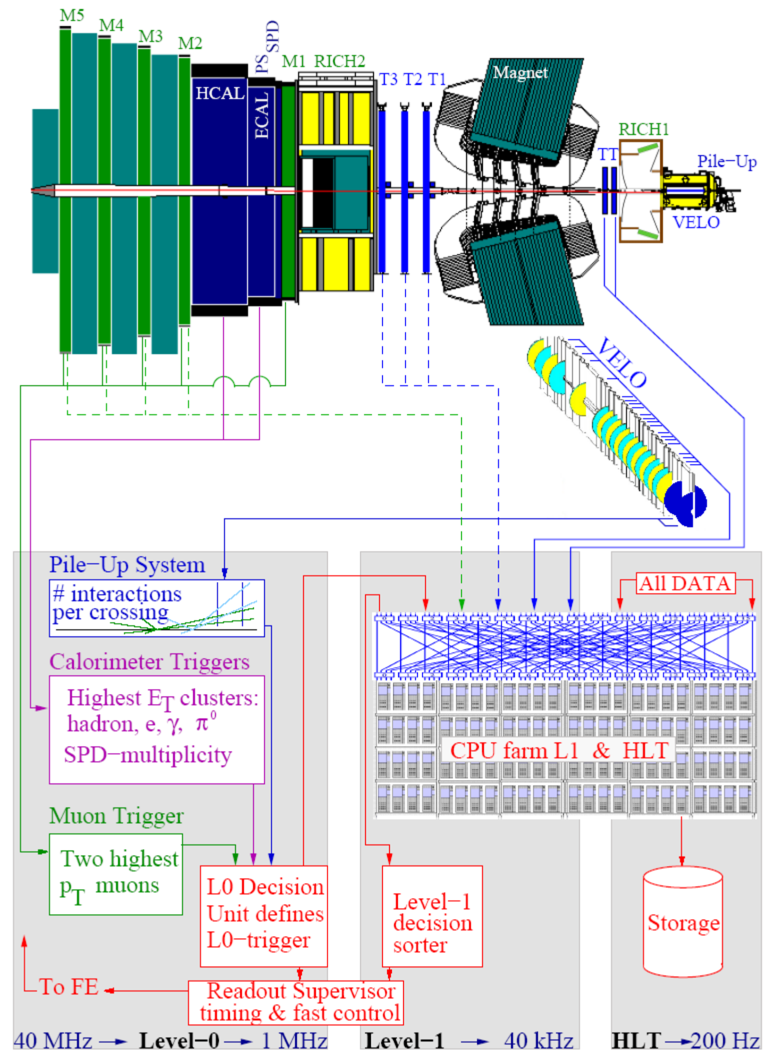
- Bandwidth:
  - regard at each stage: bandwidth = event size x output rate
  - usually limited by: available technology and cost for computing and networking
  - total bandwidth get split into fixed or tuneable “physics channels”
  - pre-scaling: reduce large contributions by known fraction to enhance rare events

Modern Example: LHCb

- Level 0:
  - 40MHz input
  - 1MHz output: 1/40 reduction
  - 4μs latency:
    - TOF+cables: <1000ns
    - processing: <1200ns
    - decision unit: <500ns
    - readout supervisor: <800ns
    - contingency: 500ns
- Level 1:
  - 1MHz input
  - 40kHz output: 1/25 reduction
  - variable latency up to 58ms
- HLT:
  - L2+L3
  - 40kHz input
  - 200Hz output to disc/tape: 1/200 reduction

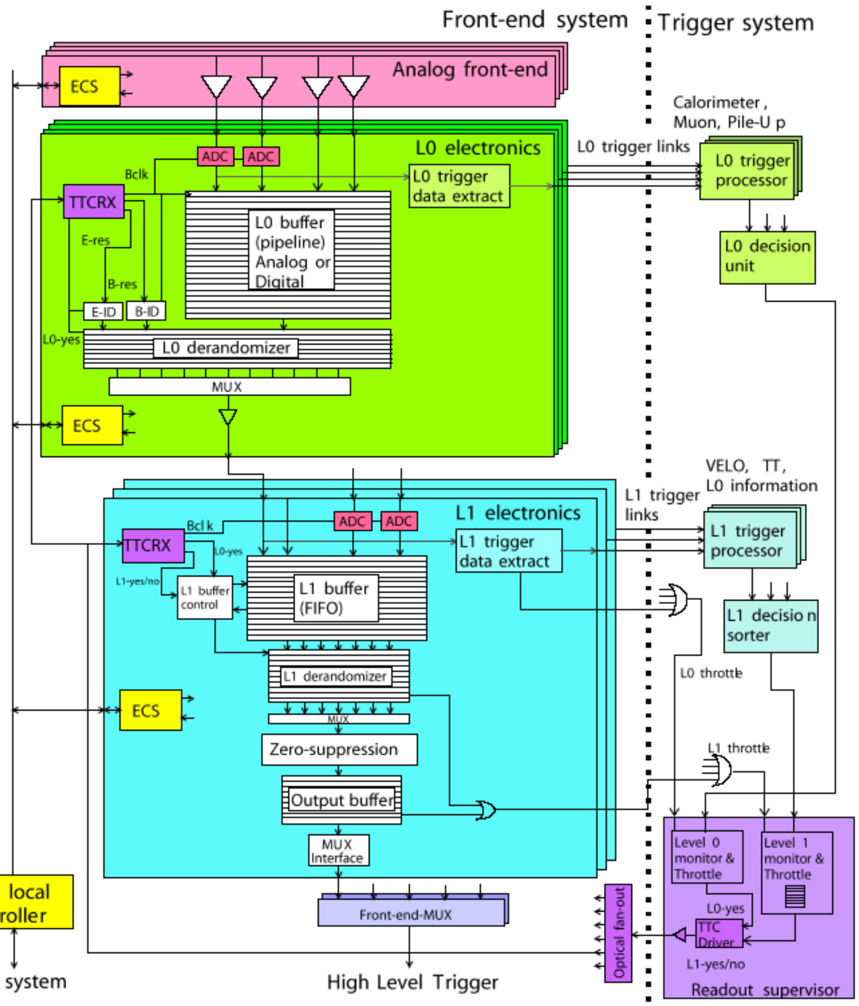


L1 efficiency of L0 selected and offline accepted events



Modern Example: LHCb

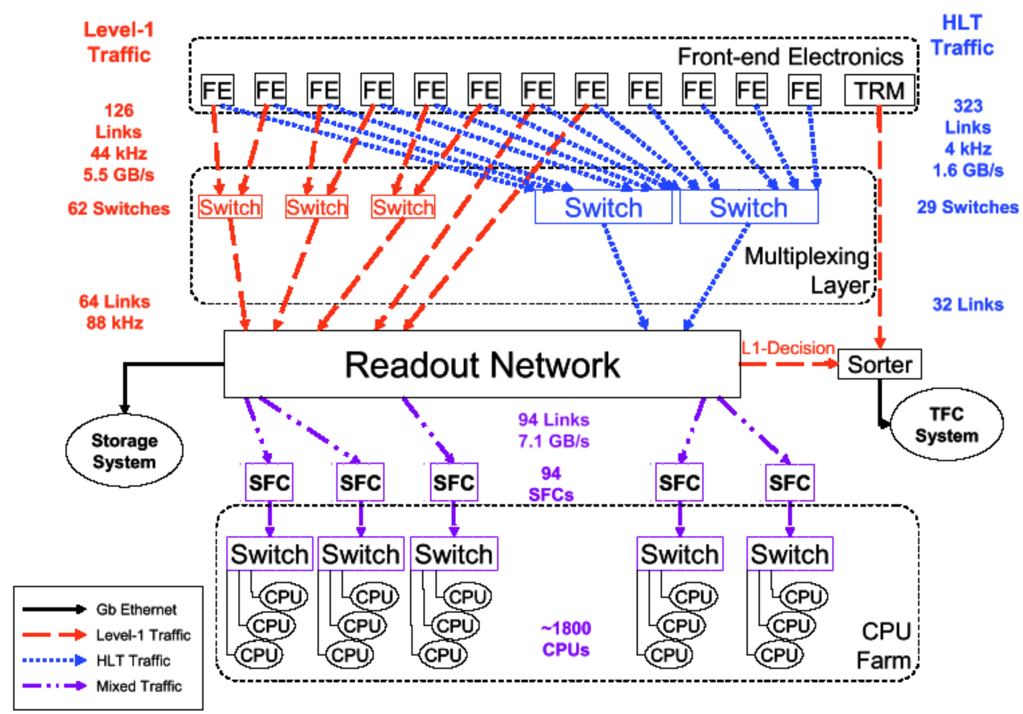
L0



L1

- derandomiser (L0 & L1):
  - synchronise date from sub-systems
- zero-suppression: @ L1
- data package sorting and packaging: @ L1

L1 L2+L3



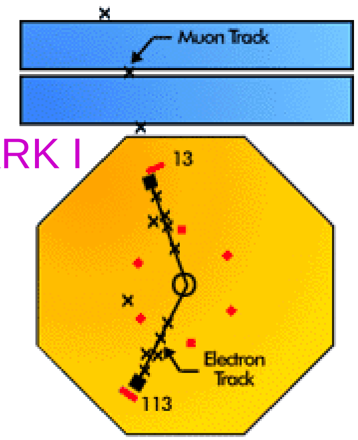
Trailer – not presented

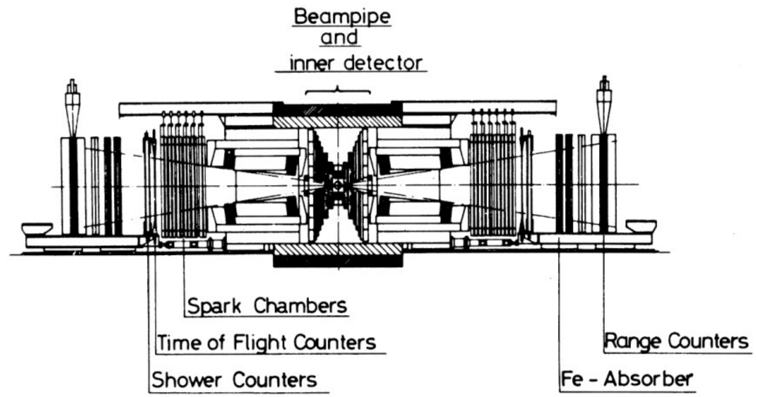
- Trailer to course:
  - beyond the time scale of the lectures…
  - summary of integrated detector concepts
  - as ideas for self-study to dig further

70’s – integrated detectors

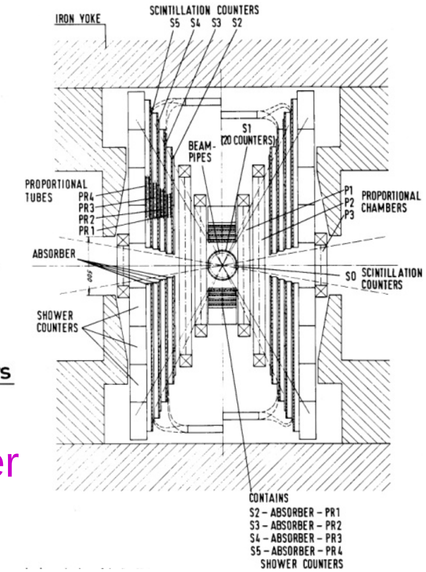
- 1973: MARK I
- 1974: DASP
- 1977: MARK II

MARK I

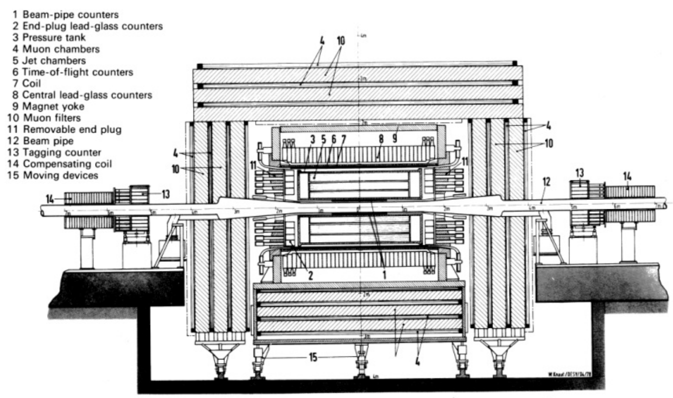




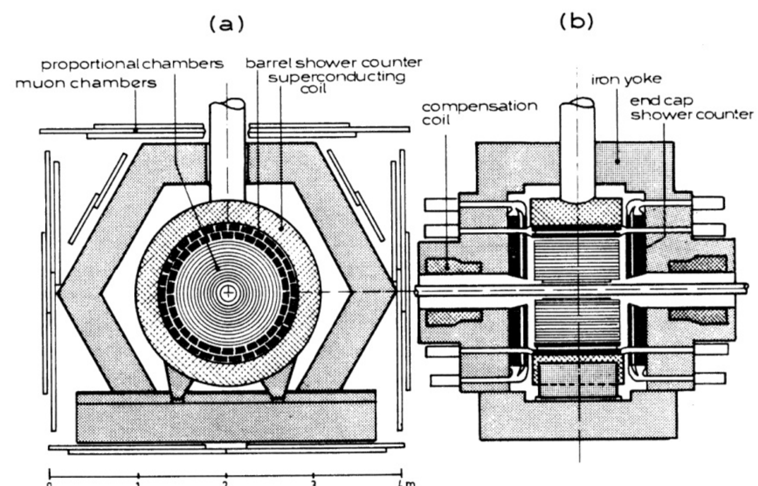
DASP – double arm spectrometer



- 1979: JADE, TASSO, PLUTO, MARK J



JADE – jet drift chamber

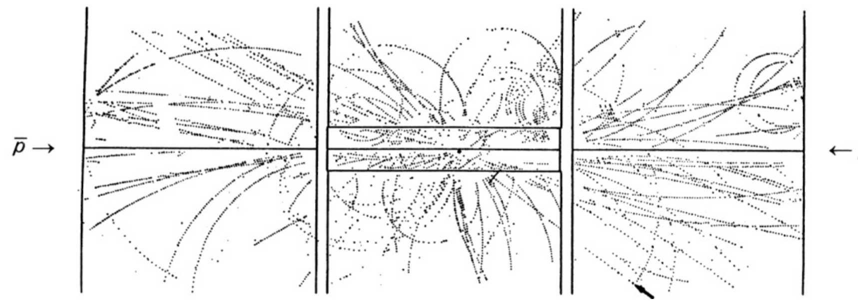


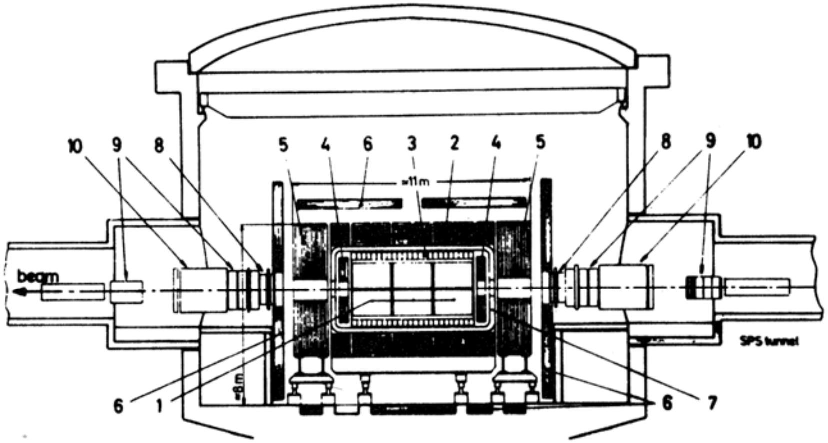
PLUTO – superconducting magnet

Vertex Detectors

- 1983: UA1 & UA2: gaseous tracking chambers

first W → eν

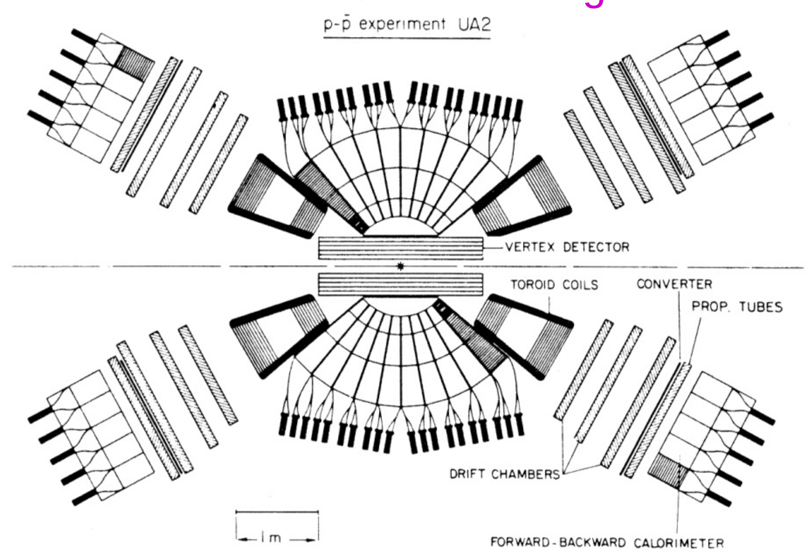




UA1 – central tracking

Fig.8.16: Seitenansicht des UA1-Detektors zum Nachweis von Proton-Antiproton-Wechselwirkungen bei 540 GeV Schwerpunktsenergie: 1. Zentraldetektor 2. und 5. Hadron-Kalorimeter, 3. und 4. Elektron-Photon-Schauerzähle: 6. Myon-Detektor, 7. Spule für Dipolfeld, 8. und 9. Kleinwinkeldetek-tor mit Kammern und Kalorimetern, 10. Kompensator-Magnete [UA1].

UA2 – vertex tracking



- 1982: SLC: silicon detectors

SLC – first CCD vertex

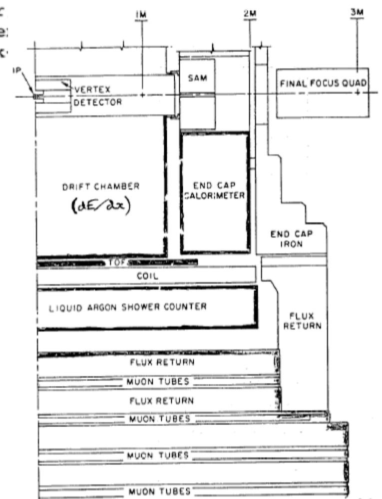
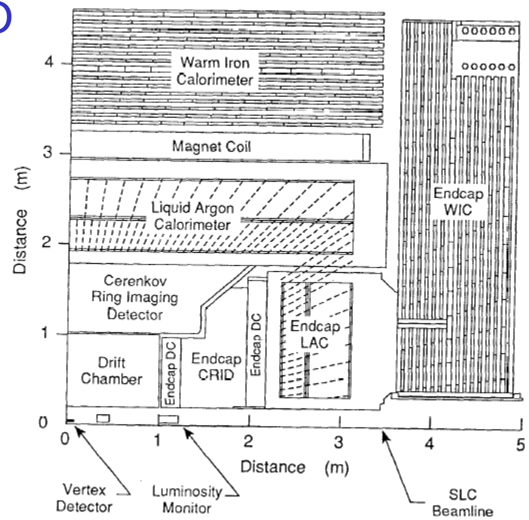


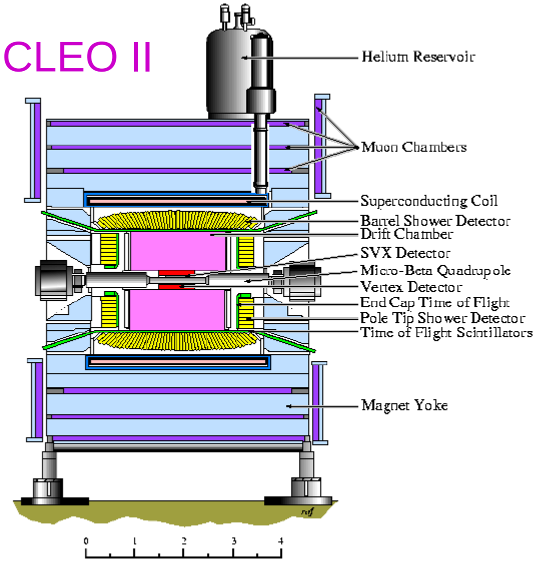
FIG. 1

SLD & CLEO

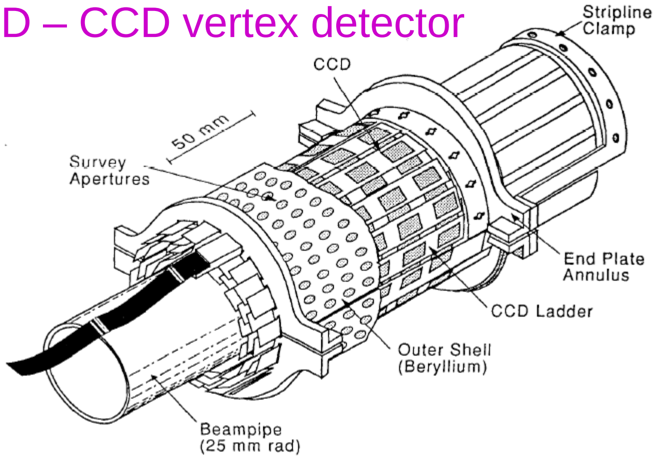
- 1982: CLEO I, 1993: CLEO II, 2001: CLEO III
- 1990: SLD



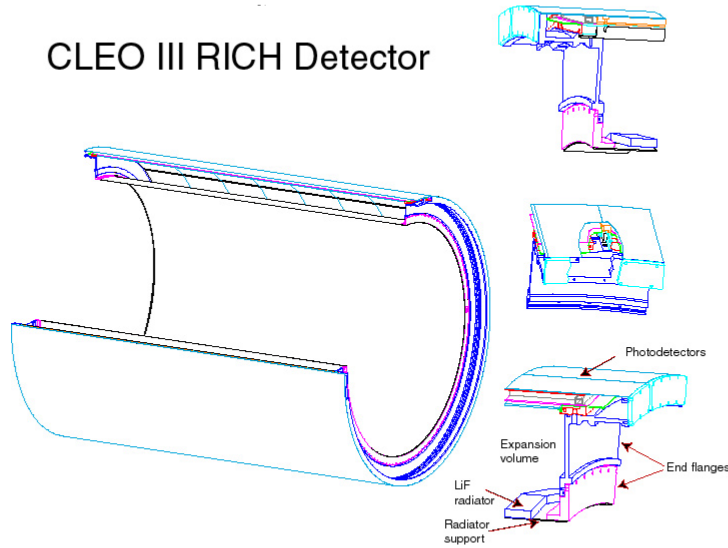
CLEO II



SLD – CCD vertex detector

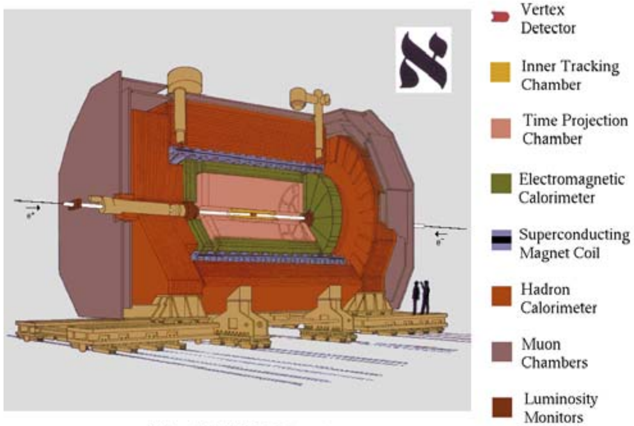


CLEO III RICH Detector

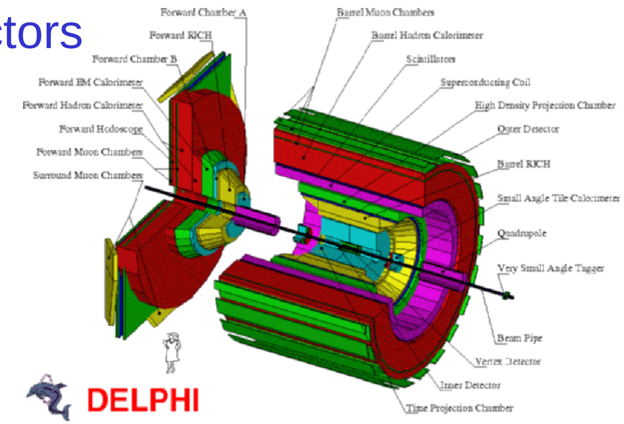


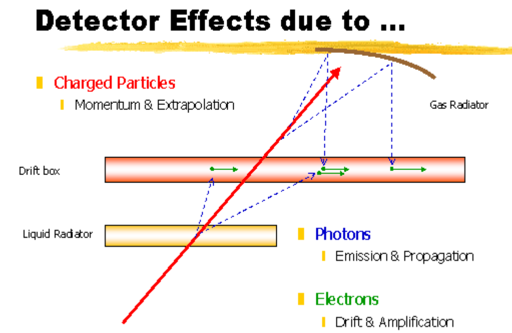
LEP

- 1989: $\sqrt{s}$ = 80-205GeV e^+e^- accellerator
- hermeticity & silicon vertex detectors

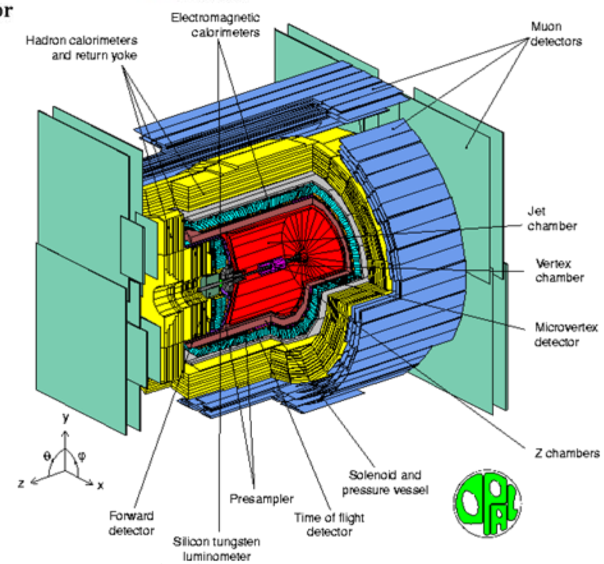


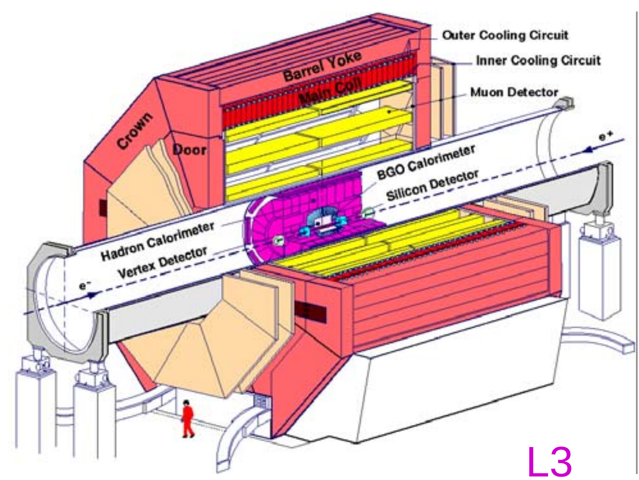
The ALEPH Detector





DELPHI - RICH



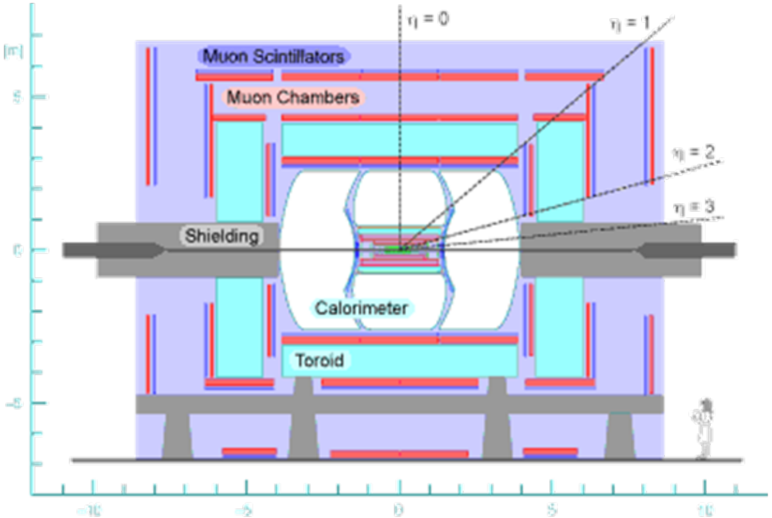


L3

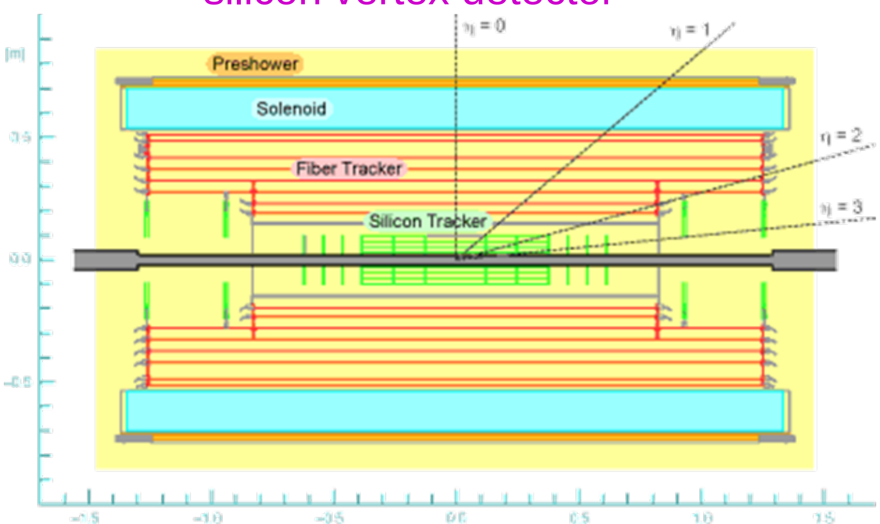
Tevatron

- 1992: $\sqrt{s}$ = 1.8TeV

D0

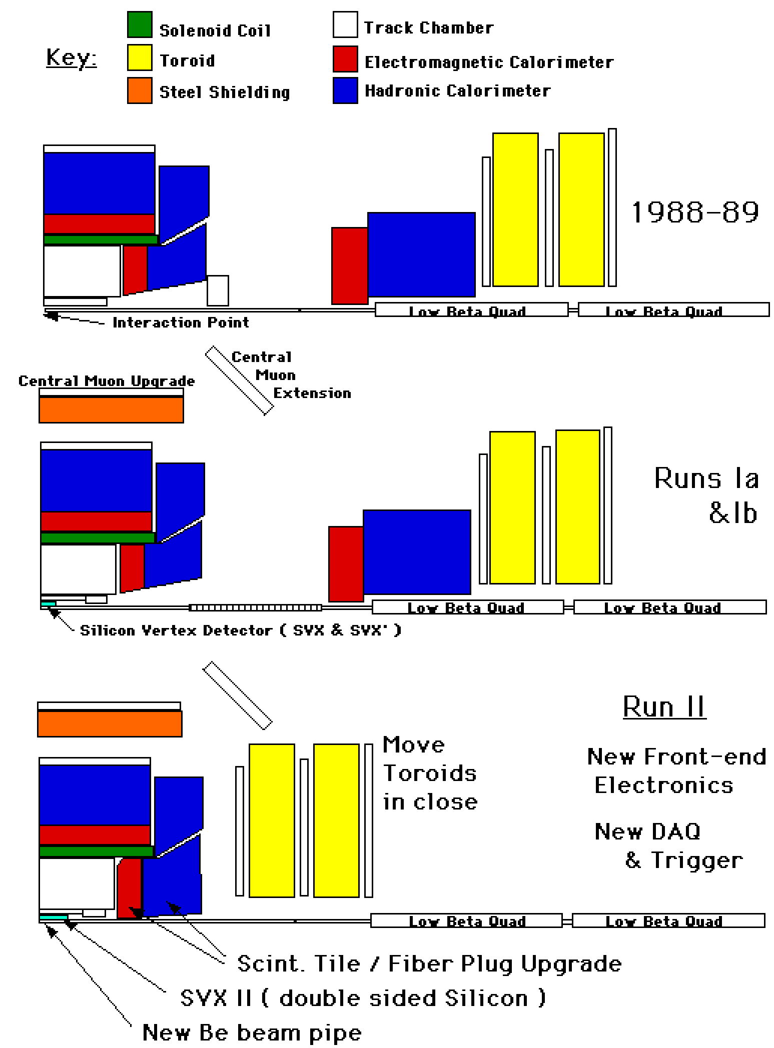


silicon vertex detector



CDF

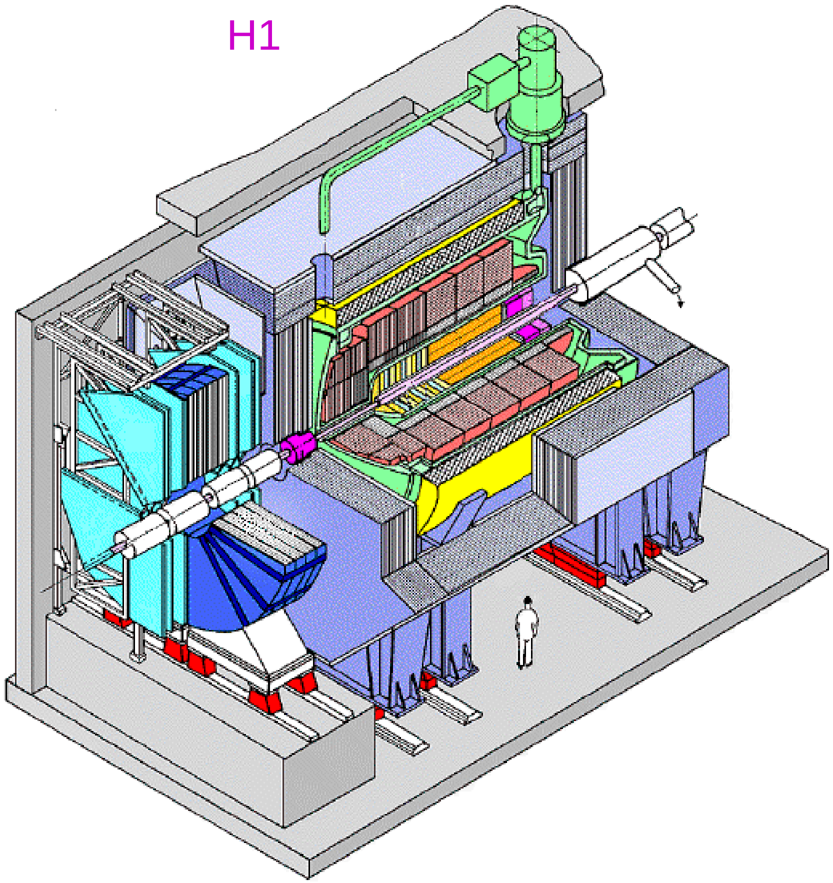
CDF Detector Evolution

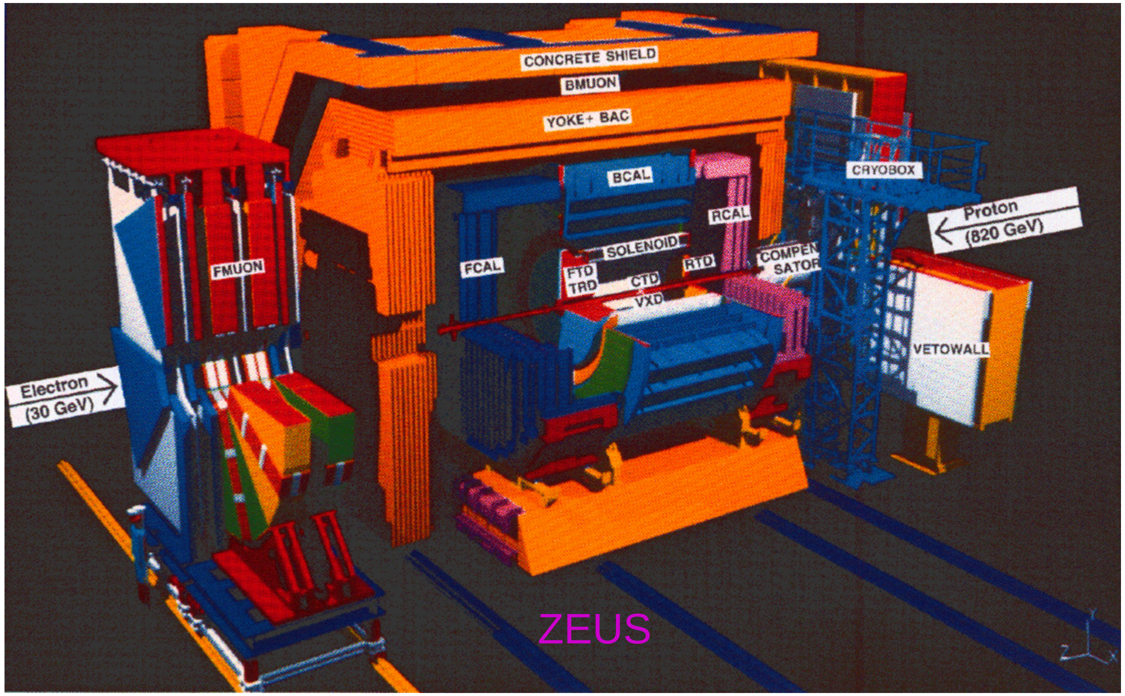


HERA

- 1992: asymmetric ep-accellerator
- hadron calorimetry

H1

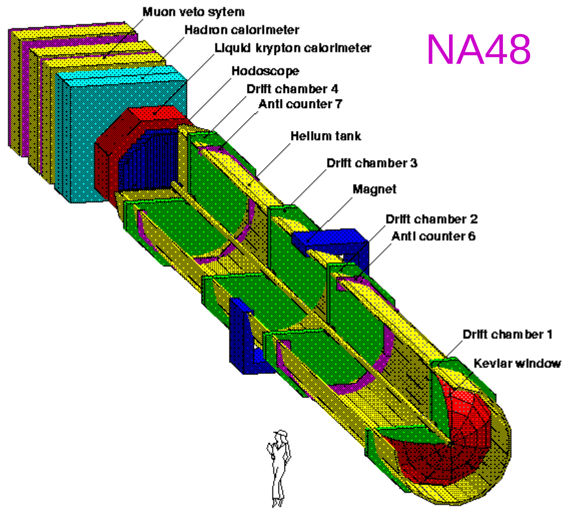




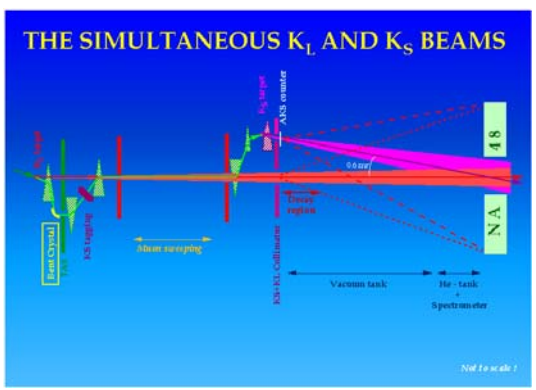
ZEUS

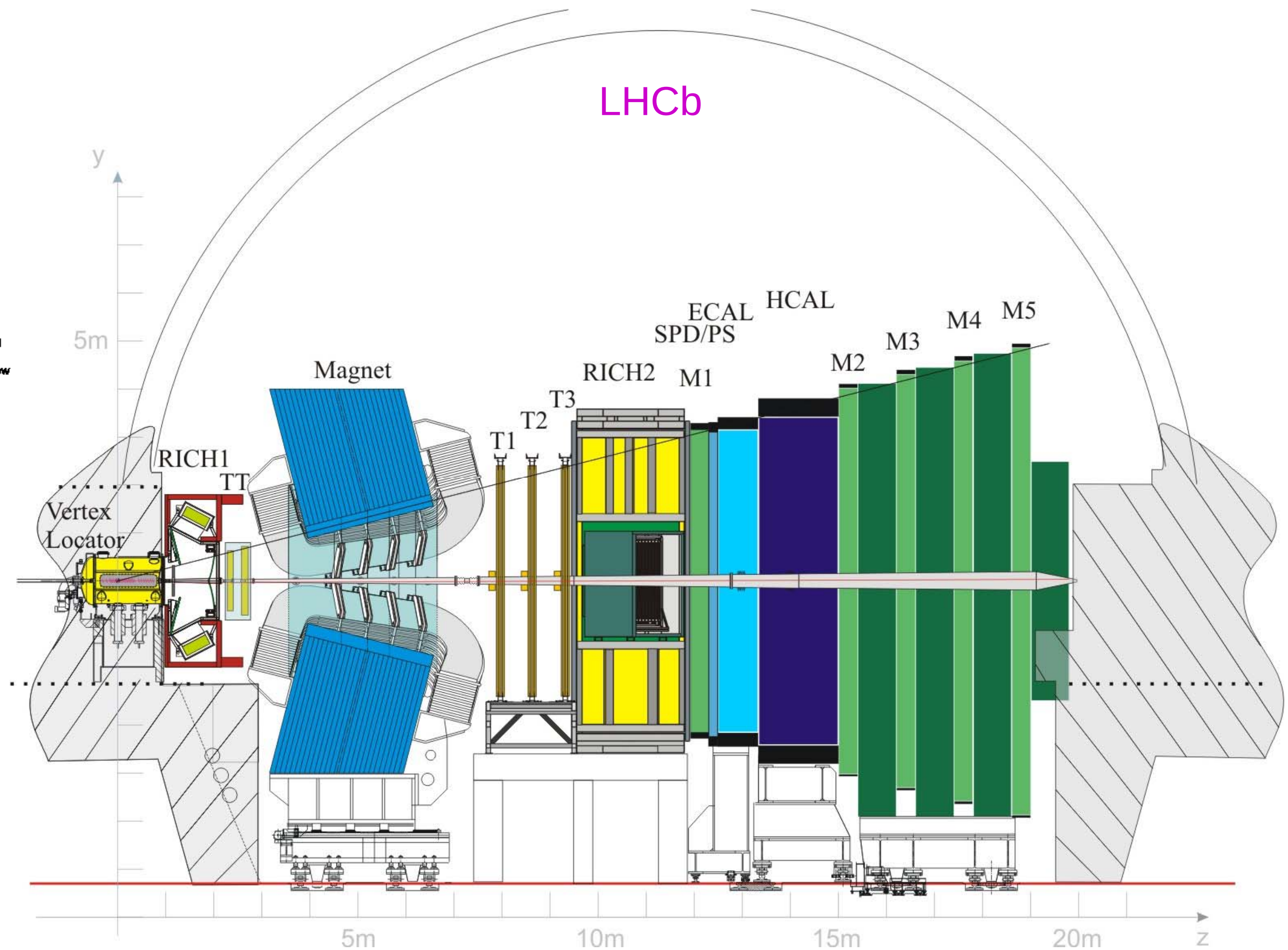
Na48 & LHCb

- fixed target experiments for precision K_0 (1997) and B_0 (2008) physics:

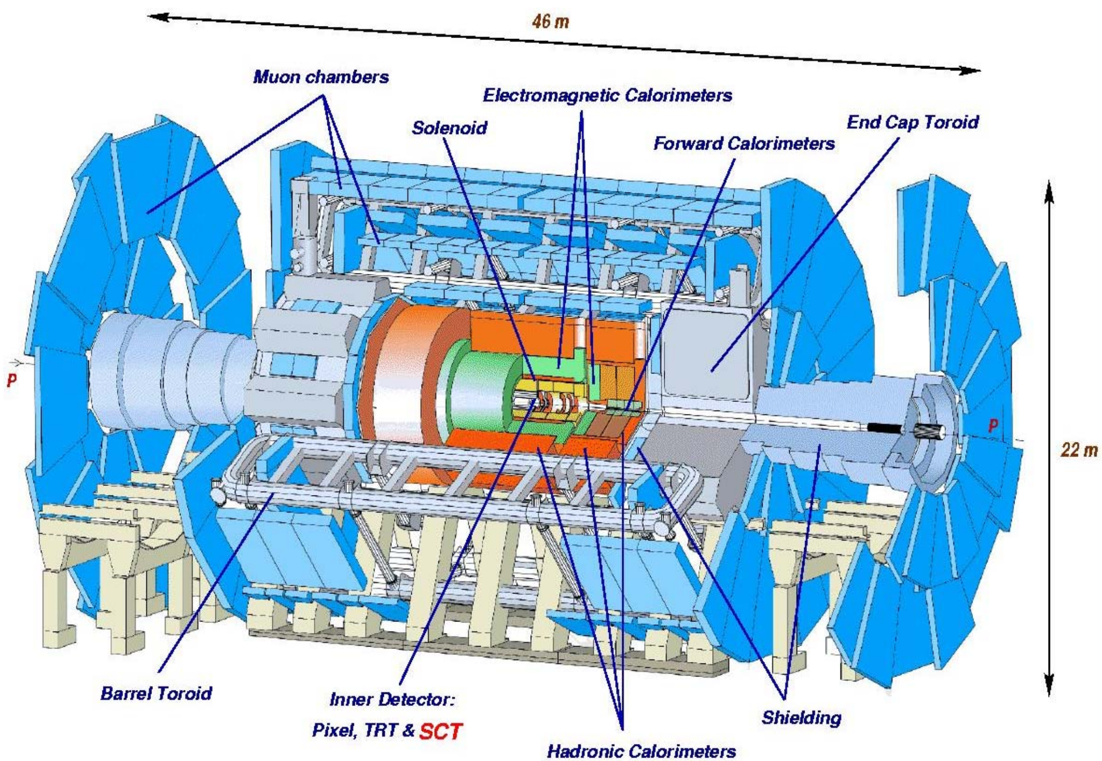


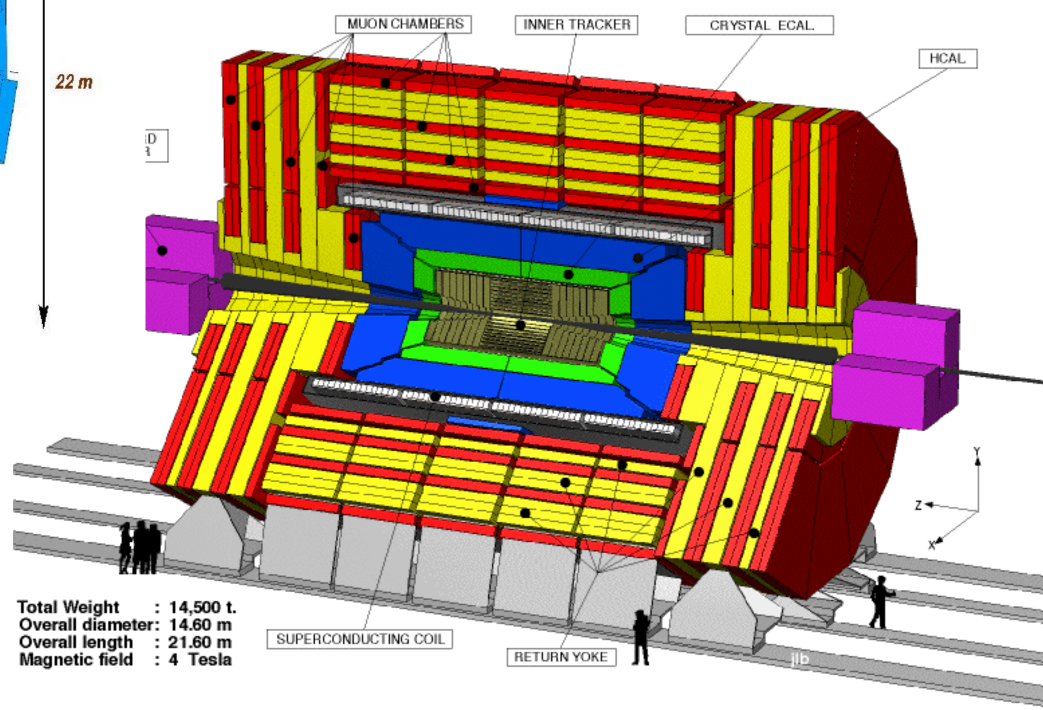
K_L & K_S beam





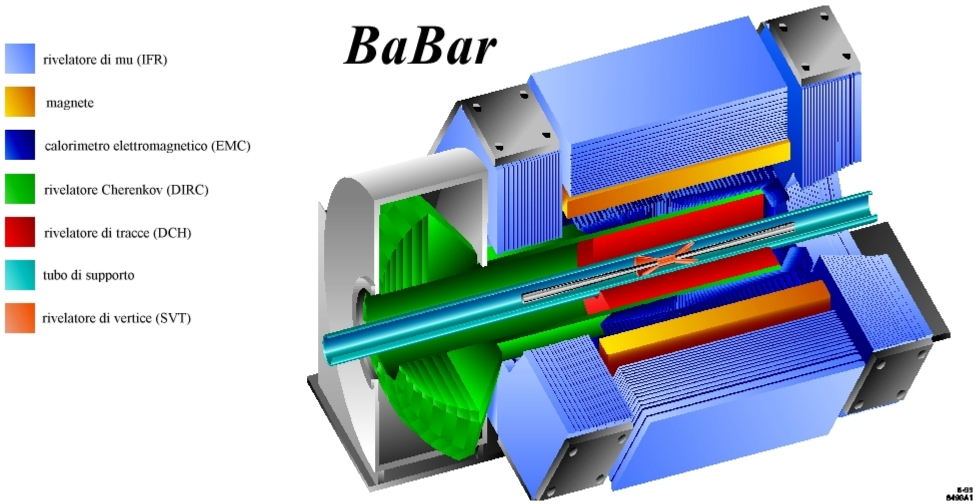
Atlas & CMS

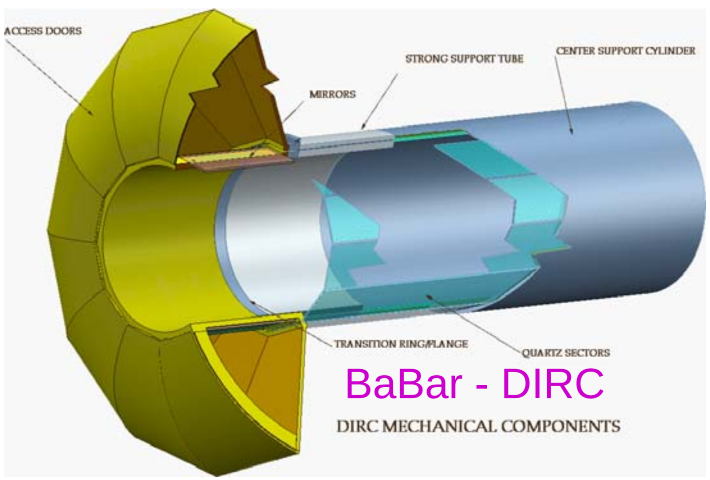

46 m
Muon chambers
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
P
P
22 m
Barrel Toroid
Inner Detector:
Pixel, TRT & SCT
Hadronic Calorimeters
Shielding


MUON CHAMBERS
INNER TRACKER
CRYSTAL ECAL
HCAL
Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla
SUPERCONDUCTING COIL
RETURN YOKE

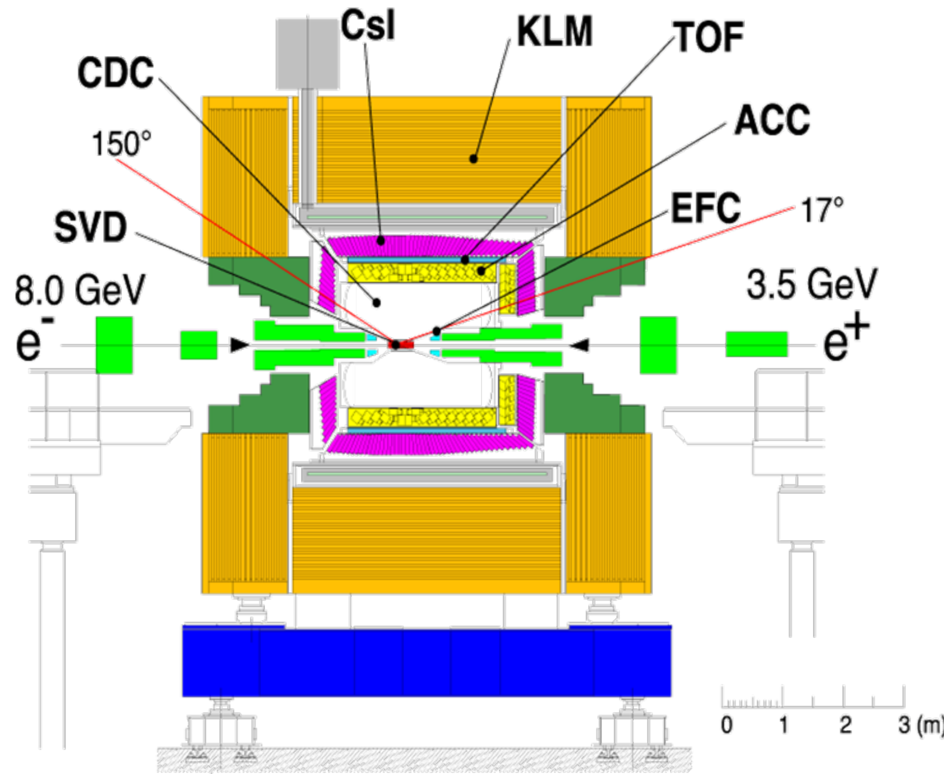
BaBar & Belle

- 2000: B – physics at asymmetric e^+e^- accellerators



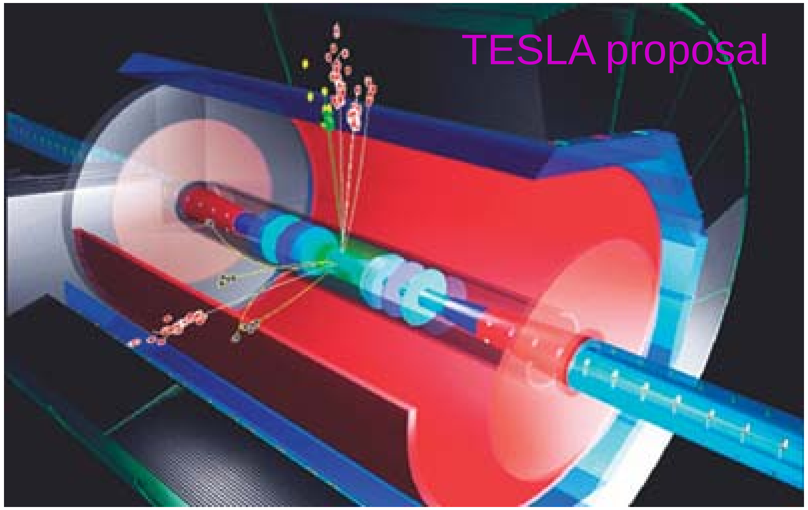


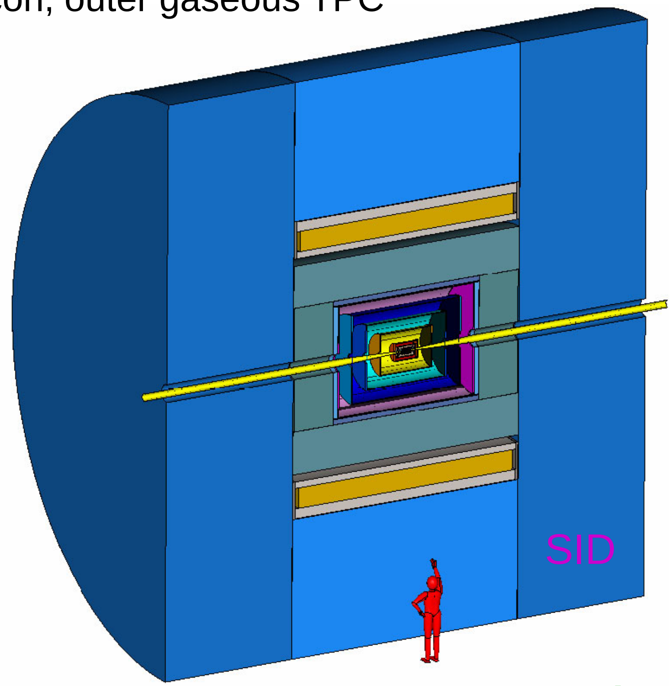
BaBar - DIRC

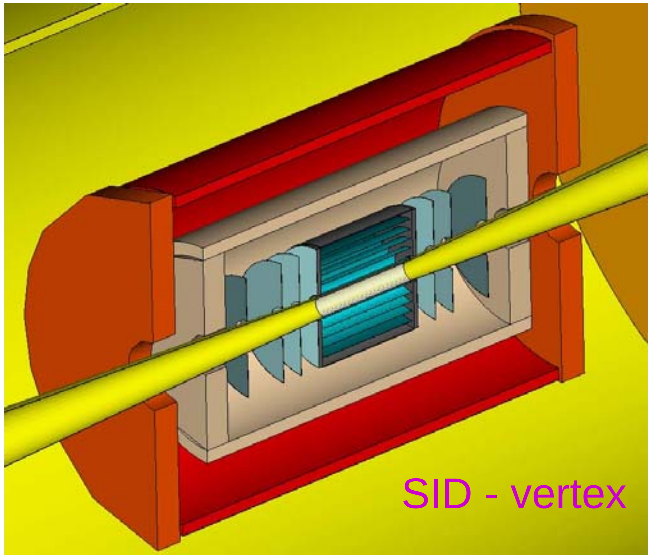


ILC Detectors

- ~ 2015: three design collaborations:
  - each is “global”
  - SiD: Silicon Detector
    - silicon only
  - LDC: Large Detector Concept
    - large gaseous TPC
  - GLC: Global Large Detector
    - inner silicon, outer gaseous TPC

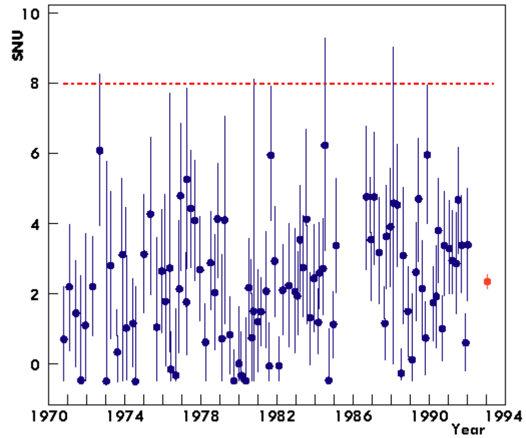


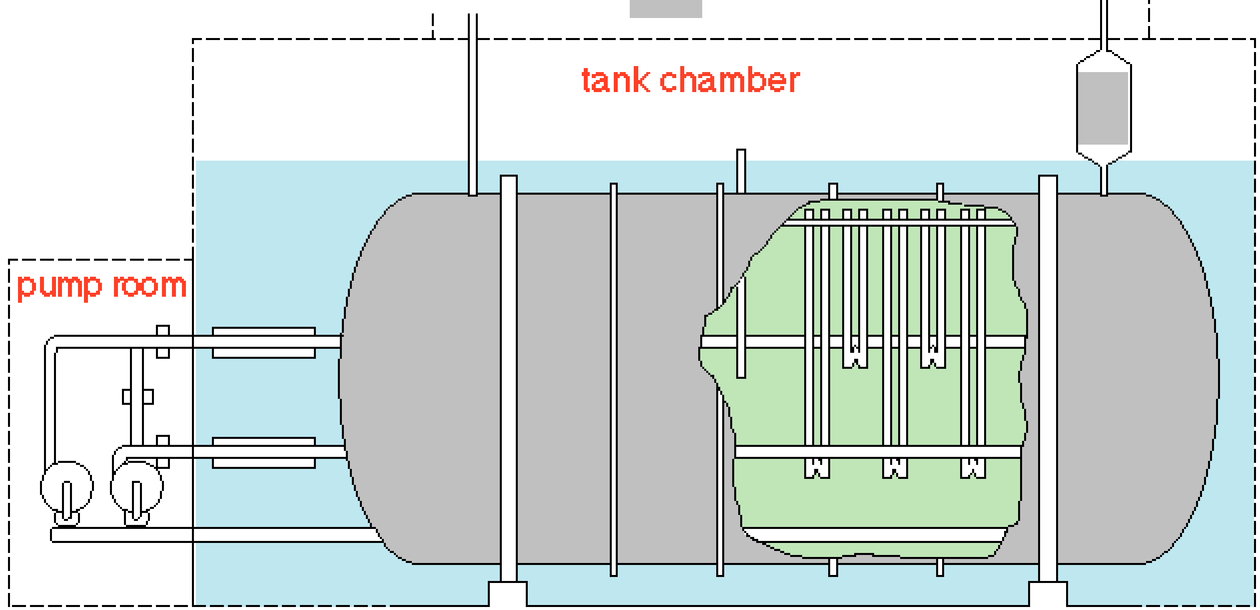




Homestake

- 1969-1993:
  - 615 tons tetrachloroethylene
  - $\nu + {}^{37}Cl \rightarrow {}^{37}Ar(\tau=35\text{days})$
  - wash O(atom) a day!



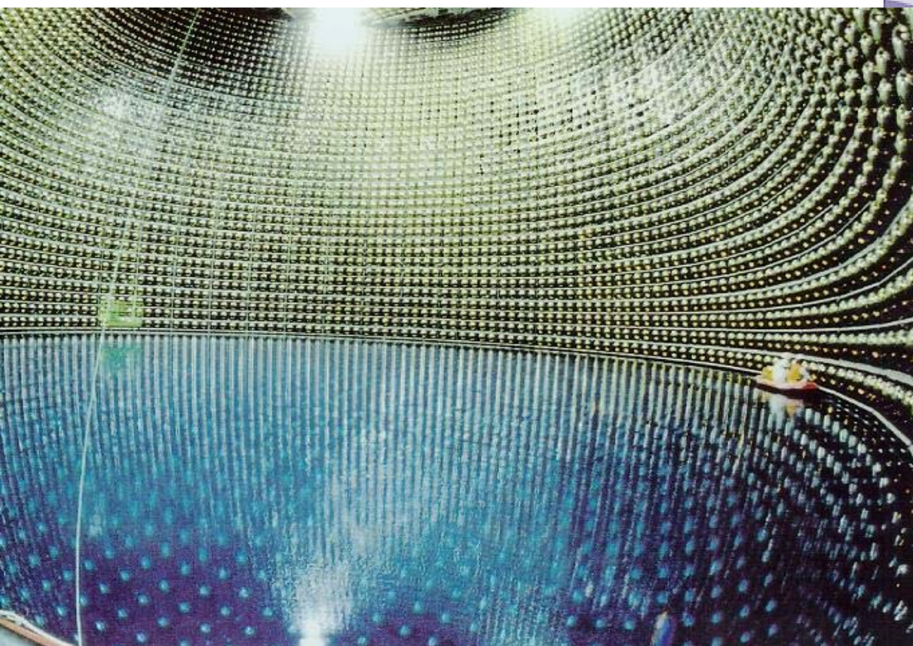


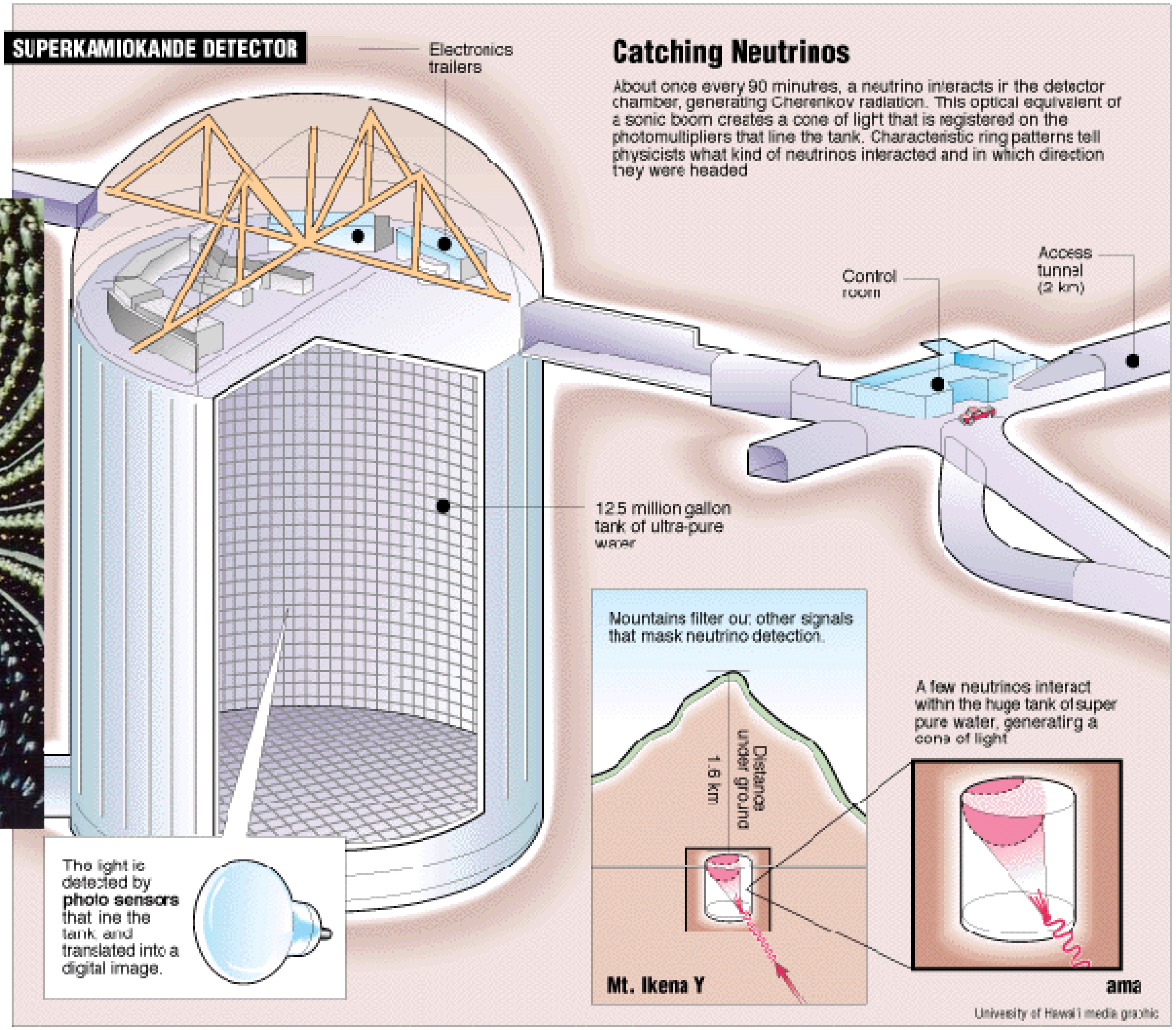
  - new: SAGE, GALLEX

Super-Kamiokande

- 1996: 50000 tons ultra-pure water
- 11146 PMT of 50cm diameter

  (1983: Kamiokande, 3000 tons, 1000 PMT)

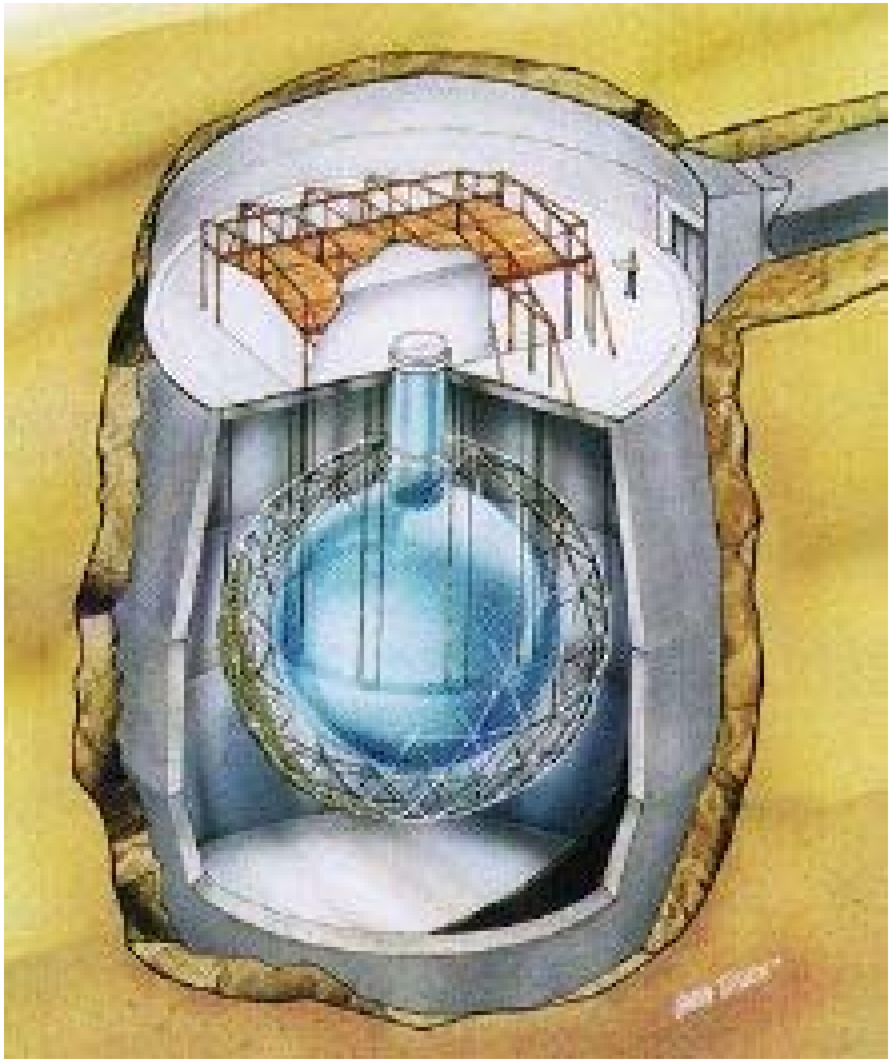


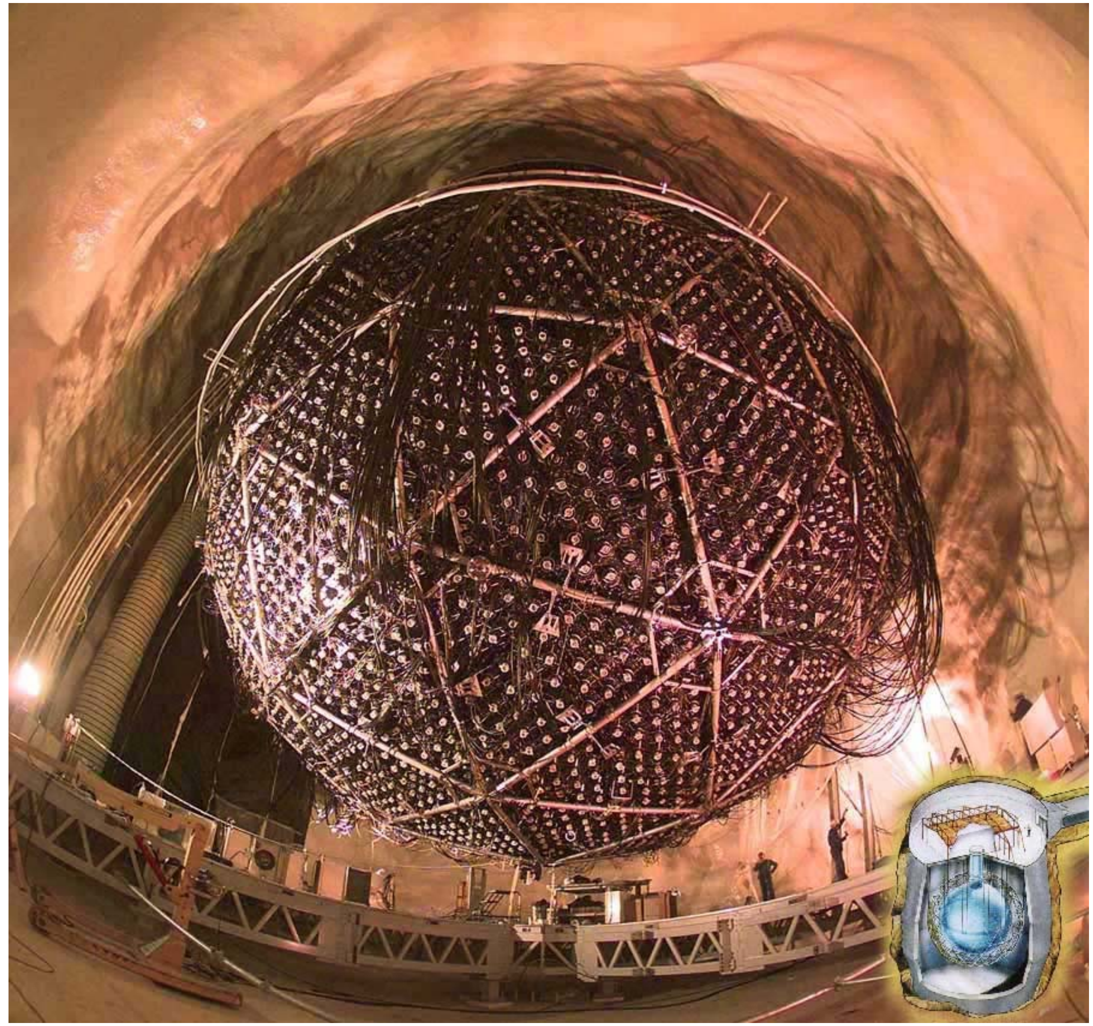


2001: implosion of 6777 PMT in chain-reaction

SNO

- 1999: Sudbury Neutrino Observatory: 1000 tons of heavy water ($D_2 0$)

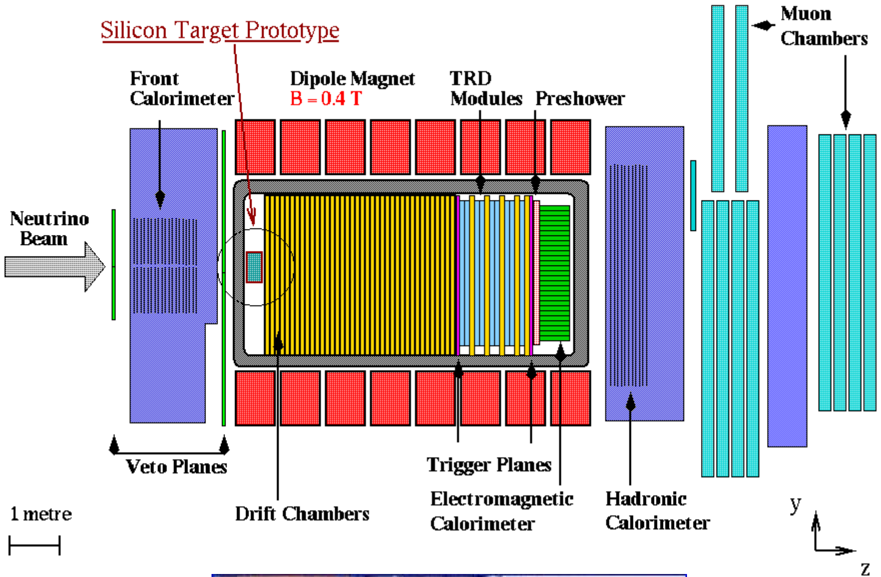


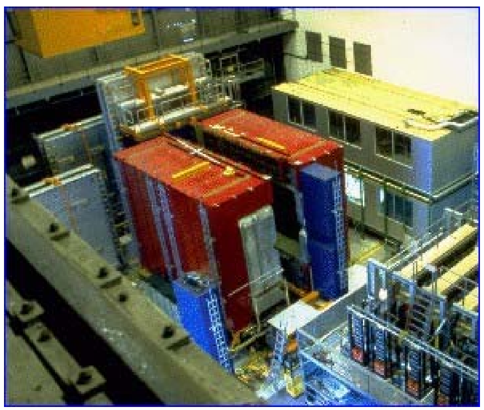


NOMAD & MINOS

1993: Neutrino Oscillation Magnetic Detector

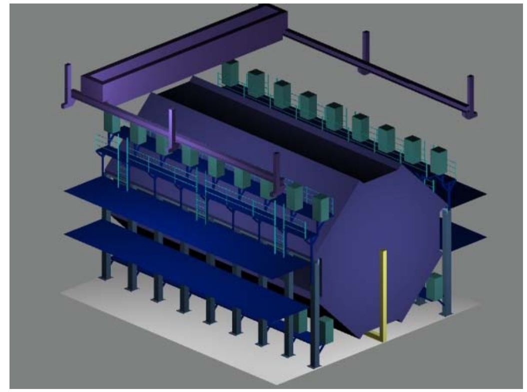
short "long base line": 835m





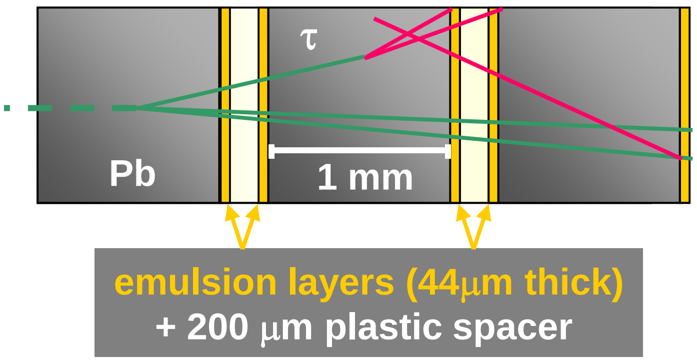
2003: Main Injector Neutrino Oscillation Search

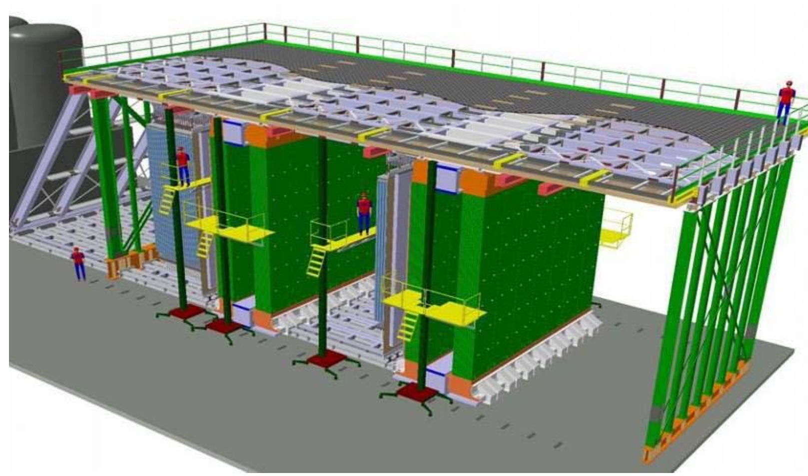
long base line: 730 km

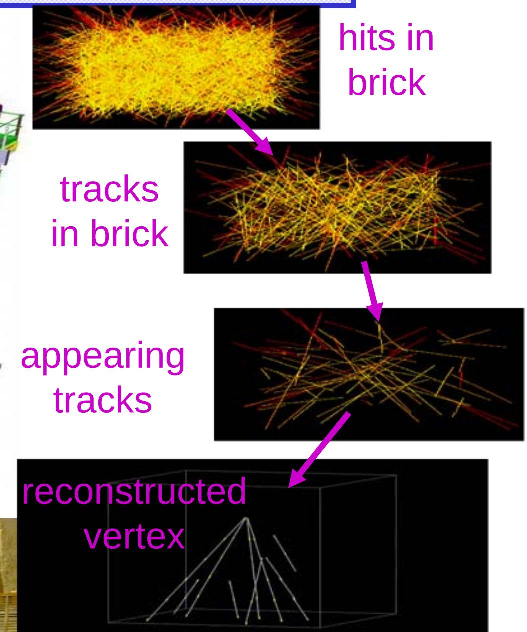


Opera

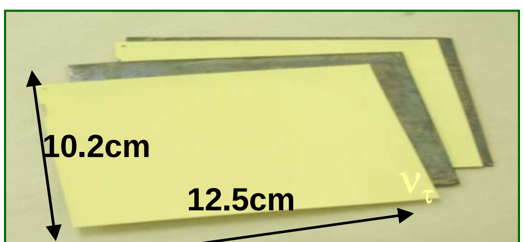
- Goal: ν_τ appearance
  - 0.15MW source
  - high energy ν_μ beam
  - long baseline:732km
  - handfuls of events/yr
- return of the nuclear emulsion



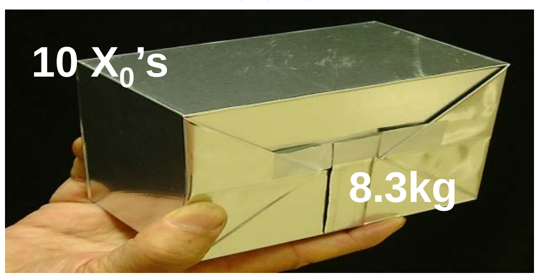




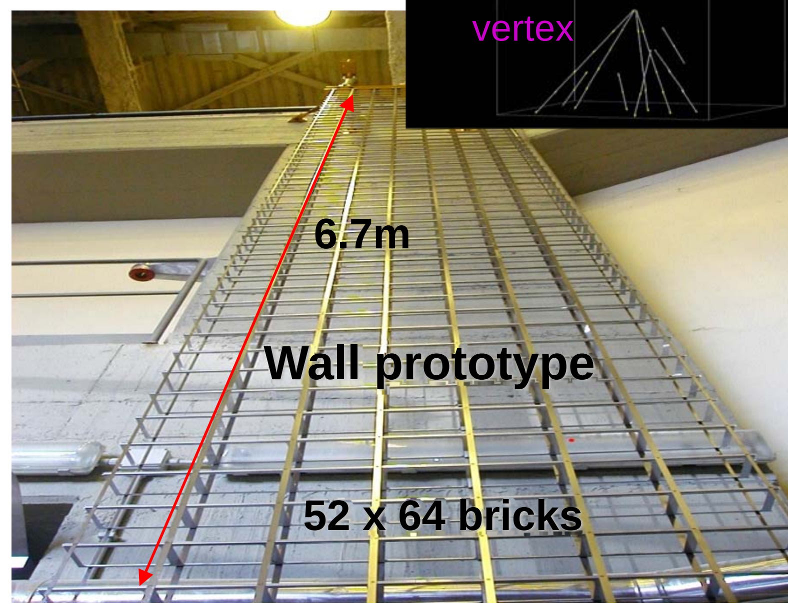
…swap brick if Scintillator trigger has noticed some tracks…



layers



BRICK: 57 emulsion foils & 56 interleaved Pb plates

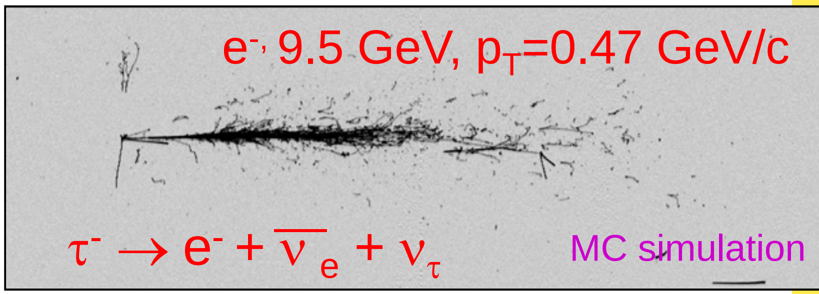


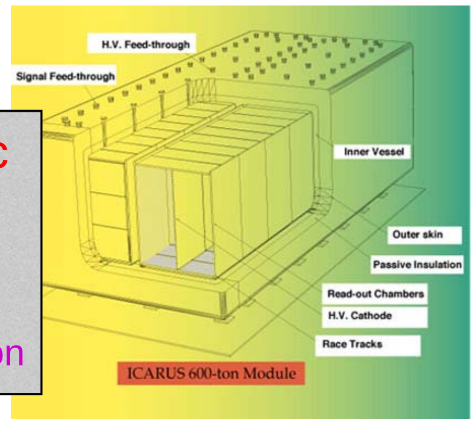
Total target mass: 1766 t

ICARUS

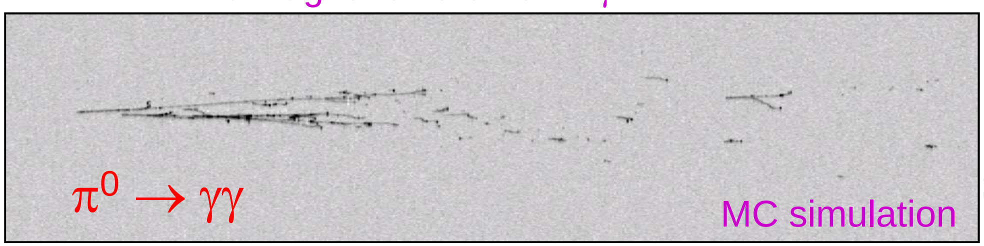
- Liquid Argon TPC: to study ν_τ appearance
  - Electronic Bubble chamber
  - Planes of wires (3mm pitch) widely separated (1.5m)
  - 55K readout channels!
  - Very Pure Liquid Argon
  - Density: 1.4, X_0=14cm λ_{had} =83cm
  - 3.6x3.9x19.1m^3 : 600 ton module (480fid)

ν_τ appearance: signature event



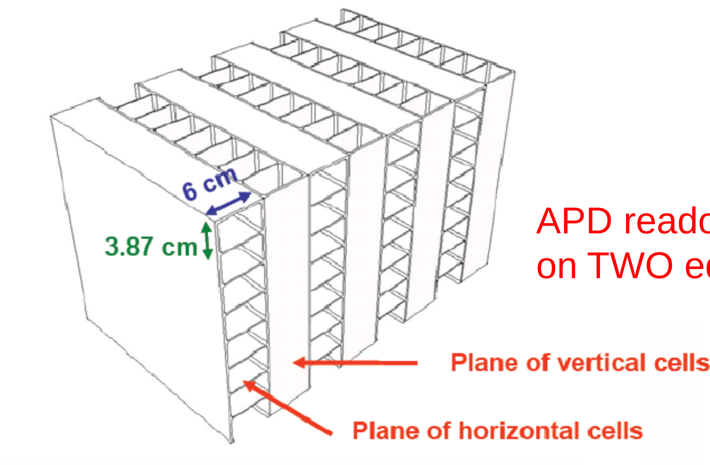


elmag. showers from 2γ



NOνA

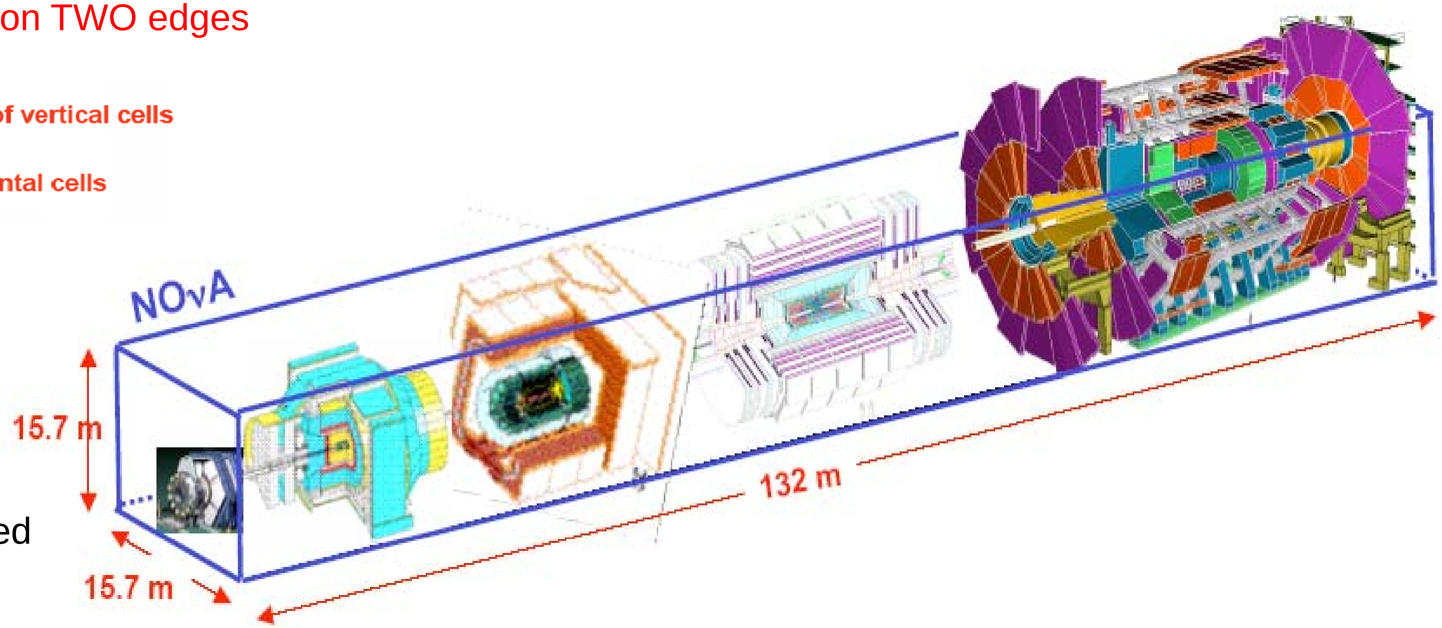
- most massive detector for $\nu_e \to \nu_\tau$ oscillation search
  - 'all' liquid scintillator (85% Sci, 15% PVC)



APD readout
on TWO edges

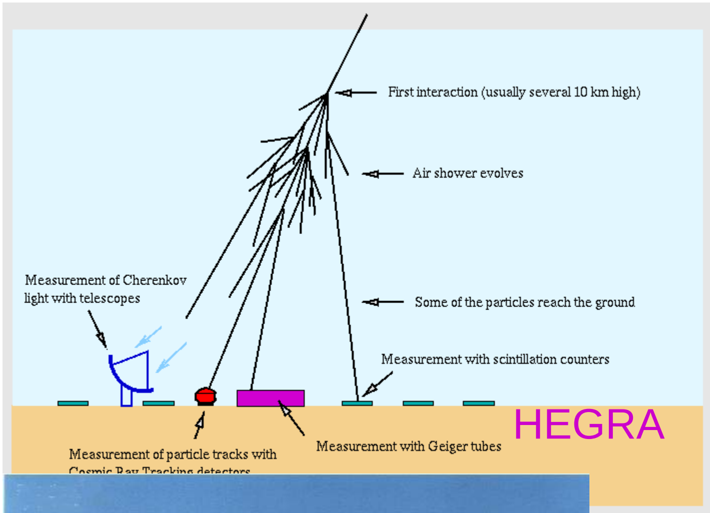
- construction & cost challenge:
  - scaling detector volume is not so trivial
  - want monolithic, manufacturabile structures
  - seek scaling as surface rather than volume if possible

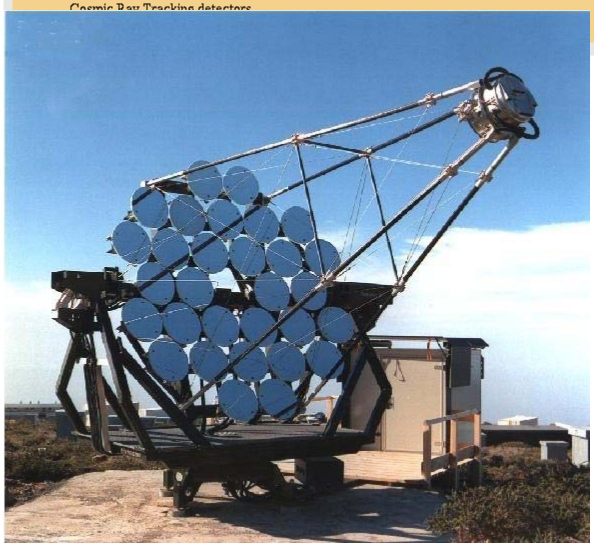
- size matters:
  - 30 ktons
  - big and massive as:
    BaBar, CDF, D0,
    CMS and ATLAS combined

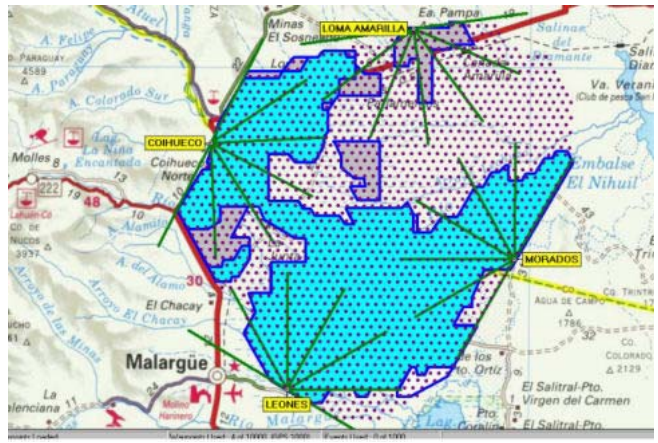


HEGRA & Auger

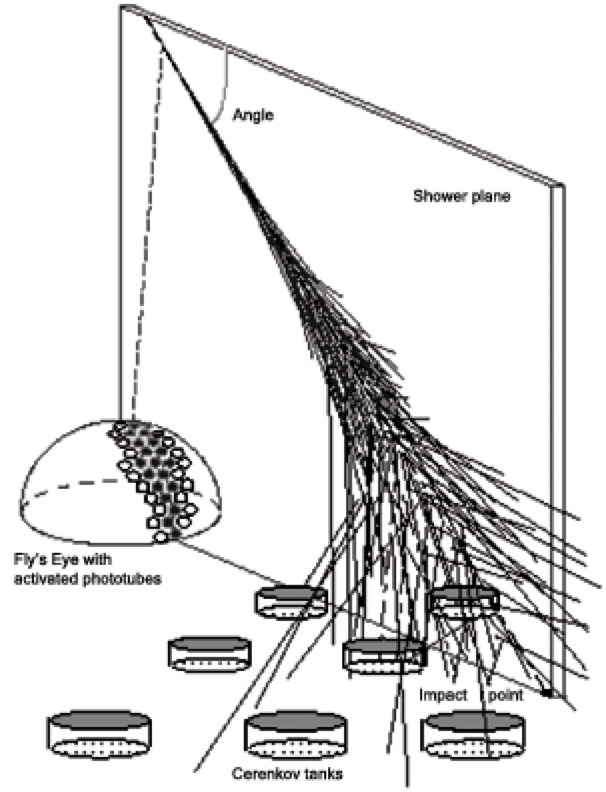
- air shower detectors:
  - 1998: HEGRA – atmospheric Cherenkov telescope
  - 2004: Auger – fluorescence & Cherenkov observatory

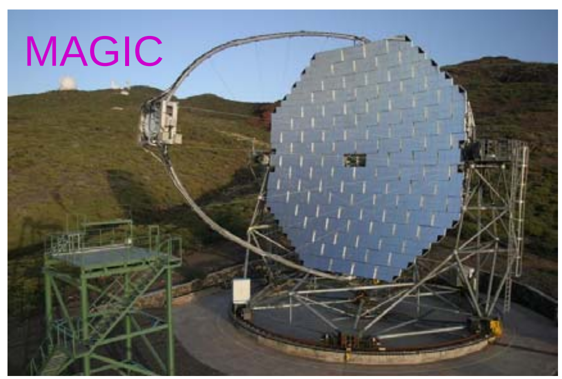






Auger





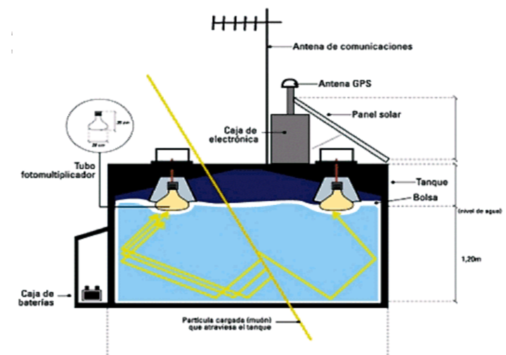
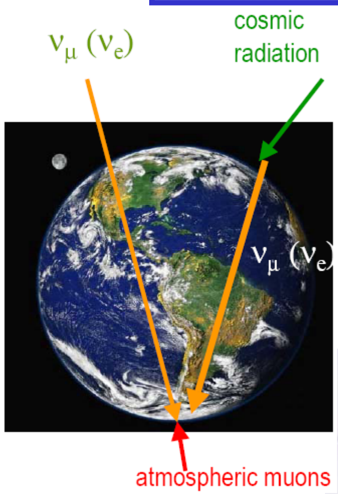
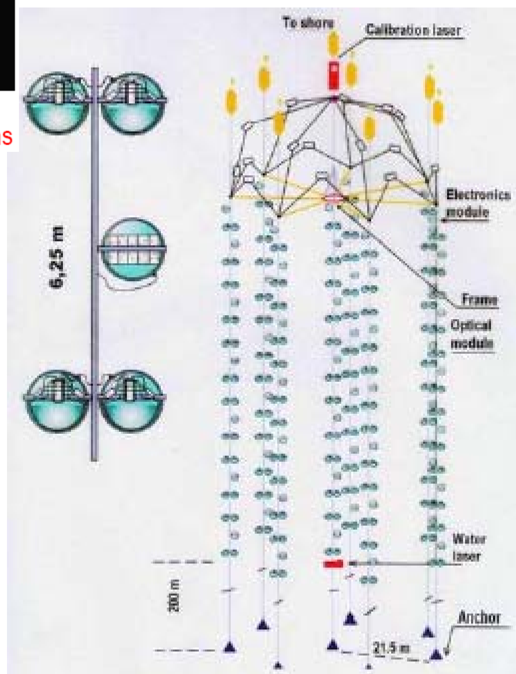


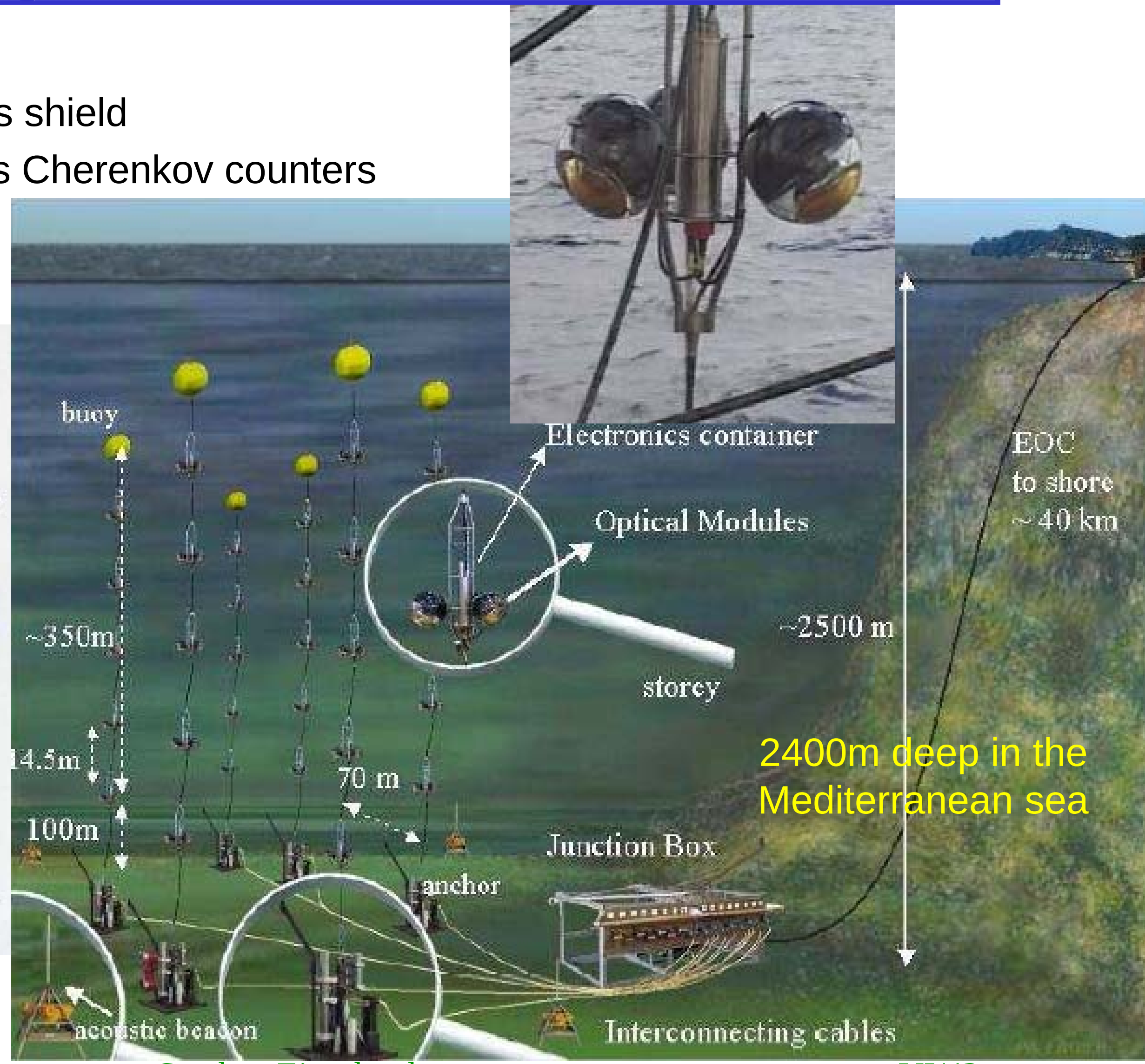
Figure 2. The water Čerenkov tank.

Baikal NT200, ANTARES & KM3Net



- ν detectors:
  - using earth as shield
  - large volumes Cherenkov counters

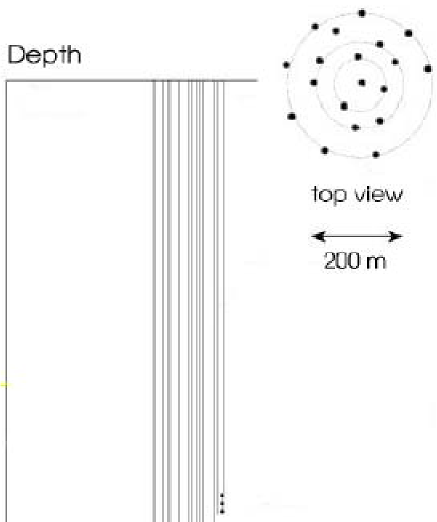


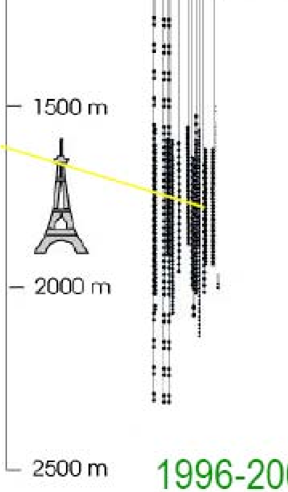


1100m deep in the Baikal lake

AMANDA & ICECUBE

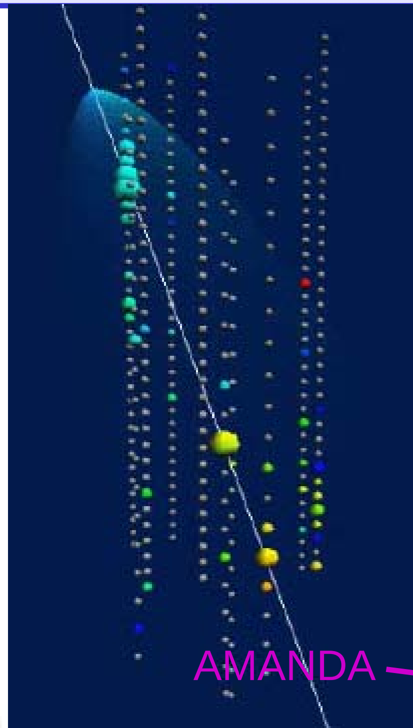
- at south pole:



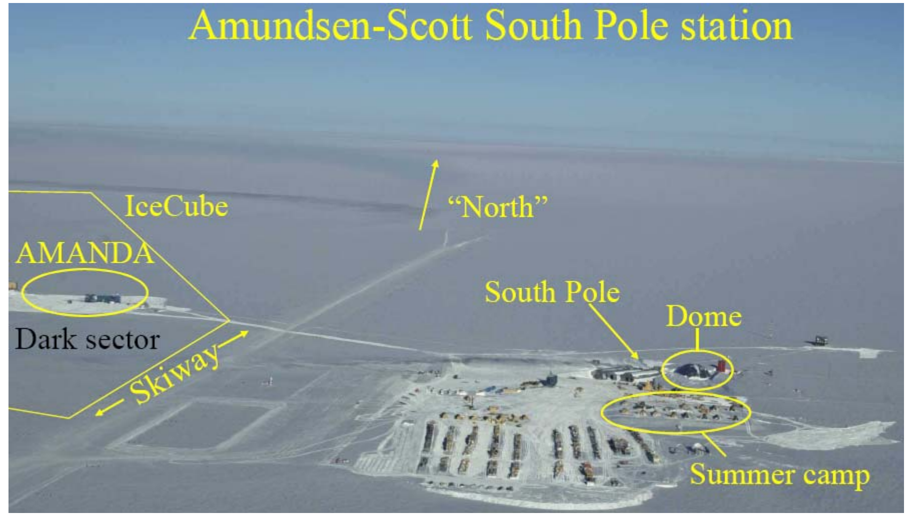


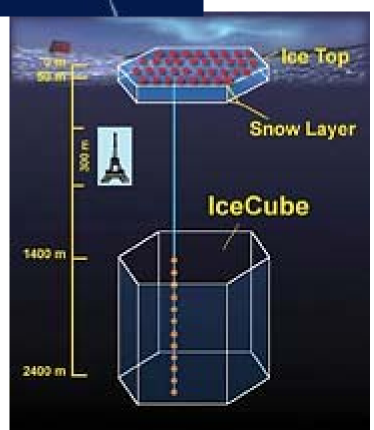
1996-2000

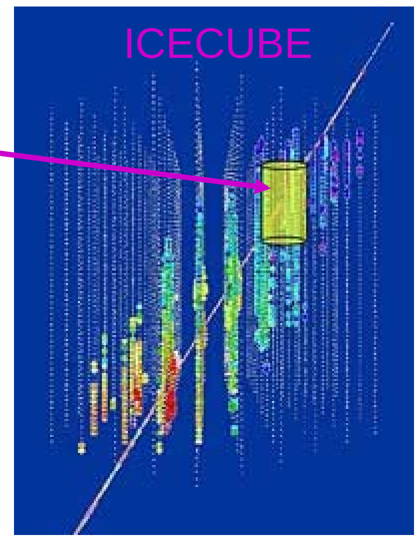
Optical module (677)



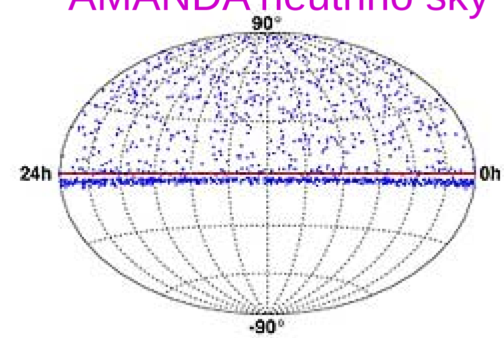
AMANDA







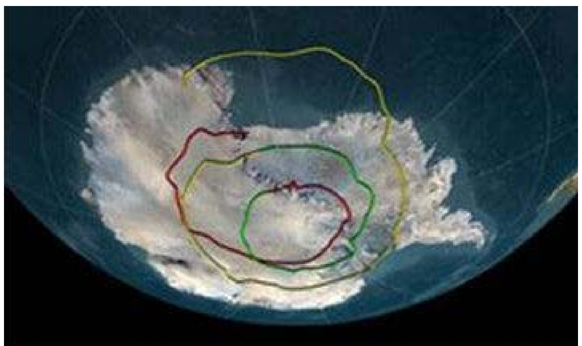
AMANDA neutrino sky

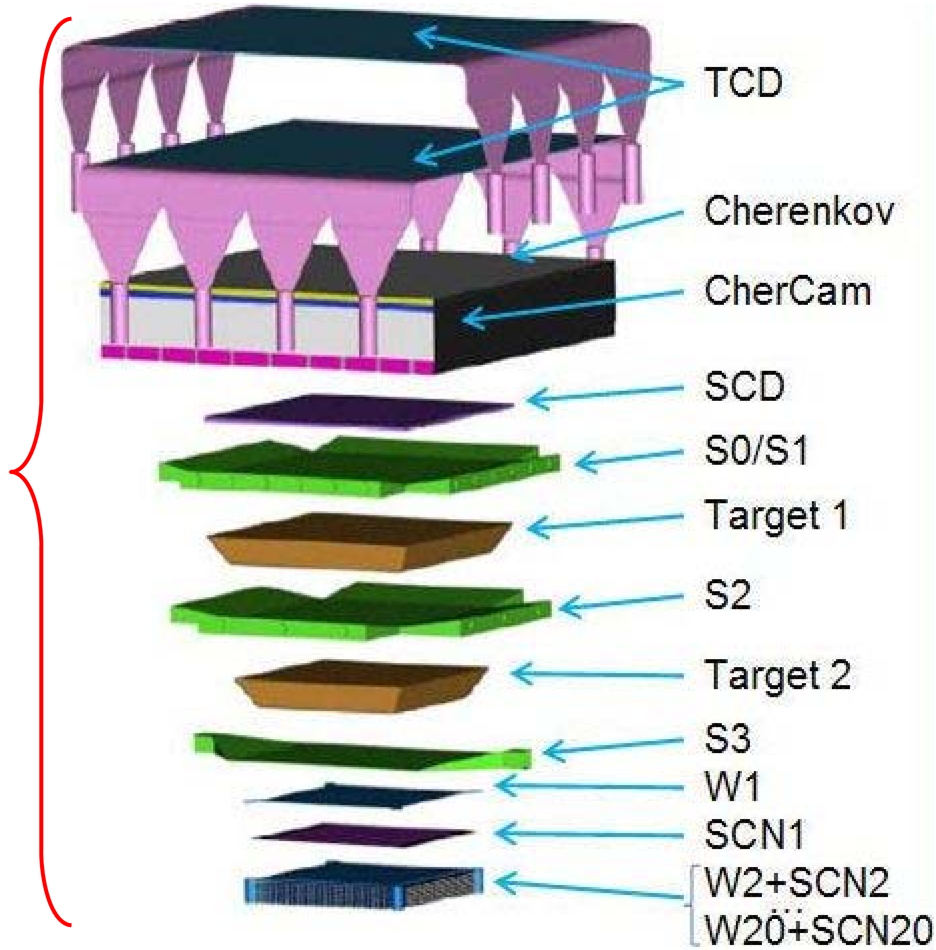


Atmosphere-bound - CREAM

- Cosmic Ray Energetics and Mass

1st CREAM flight:
16.12.05-26.01.05





Space-bound - AMS

- Alpha Magnetic Spectrometer:
  - to be mounted on ISS
  - launch: “2008”
  - particle physics detector in space:
    - antimatter
    - gamma rays
    - cold dark matter
    - earth’s particle environment
    - …